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Prospect for small-hydropower installation settled upon optimal water allocation: An action to stimulate synergies of water-food-energy nexus

Yanlai Zhou[a,c,d], Li-Chiu Chang[b], Tin-Shuan Uen[a], Shenglian Guo[c], Chong-Yu Xu[d], Fi-John Chang[a,*]

[a] Department of Bioenvironmental Systems Engineering, National Taiwan University, Taipei 10617, Taiwan
[b] Department of Water Resources and Environmental Engineering, Tamkang University, New Taipei City 25137, Taiwan
[c] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
[d] Department of Geosciences, University of Oslo, P.O. Box 1047 Blindern, N-0316 Oslo, Norway

HIGHLIGHTS

- Integrate small-hydropower into water supply systems to lift renewable power output.
- NSGA-II optimizes water reliability & ratio of water storage to reservoir capacity.
- GA suggests small-hydropower installation strategies by optimizing power output.
- Water-driven approach drives up the synergies of the Water, Food and Energy Nexus.
- Proposed methodology lifts power output/food production and mitigate water shortage.

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ABSTRACT

The incorporation of renewable power generation into existing water supply systems is known to have far-reaching influences on system operation in response to booming urbanization. This study proposed a holistic system-wide solution driven by water resources perspectives encouraging small-hydropower generation using artificial intelligence techniques to leverage the synergies of the Water-Food-Energy (WFE) Nexus. The Shihmen Reservoir and its water supply system serving the public and agricultural sectors in northern Taiwan constituted the study case. The proposed three-faceted approach was explored systematically through: optimizing multi-sectoral water allocation, maximizing the installation of small-hydropower turbines aligned with the obtained optimal multi-sectoral water allocation, and uplifting the synergistic benefits of the WFE Nexus steered by the optimal water allocation and small-hydropower installation. The findings pointed out that the derived optimal water allocation could greatly alleviate water shortage conditions and improve reservoir water retention while the acquired optimal small-hydropower installation scheme could favor hydropower output without reducing water supply to demanding sectors. Taking the M-5 operational rule curves simulation as the benchmark, the comparative results demonstrated that the multi-year joint optimization under the collaboration of water allocation and small-hydropower installation could offer mutually beneficial outcomes on the WFE Nexus: largely mitigate the average annual water shortage index by up to 40.0% (water sector), boost the average annual food production by as high as 10.6% (food sector), and lift the average annual hydropower output by 7.5% (17 million USD/yr; energy sector), respectively. This study not only opens new perspectives on cleaner energy production benefiting WFE Nexus synergies but suggests policymakers with executable strategies on small-hydropower practice in the light of sustainable development, which carves a niche in small-hydropower practice and contributes to the fulfillment of future energy needs.

1. Introduction

Water, food, and energy resources are the essential nutrients of urban centers which sustains their vibrant operation and healthy urban metabolism. Many mega-cities worldwide face great challenges in meeting the increasing demands for these nutrients due to the rapid growth in population under urbanization. The Water-Food-Energy (WFE) Nexus are inextricably interrelated, and actions in one sector

* Corresponding author.
E-mail address: changfj@ntu.edu.tw (F.-J. Chang).

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Nomenclature

Abbreviations

AFP	average annual food production
AHB	average annual hydropower benefits
AHO	average annual hydropower output of the Shihmen Hydropower Station
AI	artificial intelligence
ASHO	average annual output of small-hydropower turbines
CF	capacity factor
GA	genetic algorithm
HG	hydropower generation
kW	kilowatt
MW	megawatt
NSGA-II	non-dominated sorting genetic algorithm-II
RWS	ratio of water storage to reservoir capacity
SHP	small-hydropower plant
WFE	water-food-energy
WSI	water shortage index
WTW	water treatment work

Indices

i	index of each type of small-hydropower turbines, from 1 to K_j
j	index of small-hydropower turbine types, from 1 to M
k	index of generation, from 1 to G_{max} or g_{max}
t	index of time, from 1 to N

Parameters

D	annual operation duration of small-hydropower turbines
G_{max}	maximal generation in NSGA-II
g_{max}	maximal generation in GA
H_{total}	total of available hydraulic heads
H_{loss}	loss of hydraulic heads
I_{pop}	population size in GA
K_j	number of the type j small-hydropower turbines
M	total number of small-hydropower turbine types
N	number of ten-day periods in the whole operation time interval
n	number of years in the whole operation time interval
N_{pop}	population size in NSGA-II
P_c	crossover probability in NSGA-II
p_c	crossover probability in GA
P_m	mutation probability in NSGA-II
p_m	mutation probability in GA
R_{max}	maximal water release from the reservoir
R_{min}	minimal water release from the reservoir
S_{max}	maximal storage of the reservoir
S_{min}	minimal storage of the reservoir
V	maximal reservoir capacity
η	efficiency coefficient of a small-hydropower turbine
ρ	density of water
g	gravity acceleration
θ_{IR}	ratio of water releasing from the reservoir to irrigation sectors
θ_{PUB}	ratio of water releasing from the reservoir to public sectors
Δt	time-step, at a scale of ten days

Variables

$DT(t)$	total water demand in the t-th ten-day period
$D_{IR}(t)$	water demand of irrigation sectors in the t-th ten-day period
$D_{PUB}(t)$	water demand of public sectors in the t-th ten-day period
$H_{i,j}(t)$	ith hydraulic head at the j-th type of turbines in the t-th ten-day period
$H_{max,j}$	maximal hydraulic head of the j-th type of turbines
$H_{min,j}$	minimal hydraulic head of the j-th type of turbines
$I(t)$	inflow of the reservoir in the t-th ten-day period
I_0	initial parent population in GA
I_k	k-th intermediate population in GA
$P_{i,j}(t)$	i-th power output at the j-th type of turbines in the t-th ten-day period
	maximal power output of the j-th type of turbines
P_0	initial parent population in NSGA-II
P_k	k-th intermediate population in NSGA-II
$Q_{i,j}(t)$	i-th turbine inflow at the j-th type of turbines in the t-th ten-day period
$Q_{max,j}$	maximal water flow of the j-th type of turbines
Q_0	offspring population in NSGA-II
Q_k	k-th offspring population in NSGA-II
$R_{total}(t)$	total water release from the reservoir in the t-th ten-day period
$R_{IR}(t)$	water release from the reservoir to irrigation sectors in the t-th ten-day period
$R_{PUB}(t)$	water release from the reservoir to public sectors in the t-th ten-day period
$R_{ECO}(t)$	water release from the reservoir for satisfying basic eco-flow of the river in the t-th ten-day period
$R_{SP}(t)$	water release from the spillway of the reservoir in the t-th ten-day period
$\alpha(t)$	ratio of operation duration in the t-th ten-day period to D
$S(t)$	storage of the reservoir in the t-th ten-day period
ST(t)	total water shortage in the t-th ten-day period
S_0	offspring population in GA
S_k	kth offspring population in GA

influence the others [1]. The nexus approach can enhance the understanding of cross-sectoral interlinkages and strengthen cross-sectoral collaboration, upon which policy coherence across sectors is critical for sustainable and efficient utilization of resources. However, poor sectoral coordination and institutional fragmentation have driven an unsustainable use of resources, which would inevitably threaten WFE security [2]. It stresses the need for a major evolution in the decision-making process of WFE resources allocation toward a holistic view and the development of institutional mechanisms for settling the actions of diverse stakeholders and leveraging synergies [3,4]. Understanding the dynamic linkages among these crucial resources as well as upgrading their use efficiency could achieve a win-win situation for human well-being worldwide [5,6]. There are a variety of literatures investigating the WFE Nexus from the perspectives of energy generation, food production and water resources management using various advanced techniques [7], for instance, supply chain analysis [8,9], water-carbon footprint [10], life cycle assessment [11], system dynamic simulation [12,13], and artificial intelligence (AI)-based reservoir operation [14,15]. In particular, AI-based reservoir operation has been one of the most promising approaches to lifting the collaborative benefits of the WFE Nexus [16,17].

Hydropower generates electricity using the force of moving water, which neither consumes water resources nor causes air pollution. Hydropower nowadays represents a source of renewable energy. Despite safe exploitation of the water resources for hydropower generation, large hydro projects, however, met with substantial opposition in consideration of environmental and social implications such that slowdowns in hydroelectricity generation occurred between the late 1990s and the early 2000s [18,19]. Nevertheless, obstructing large hydropower projects would not reduce energy demands. Thus, requests for the rehabilitation and repowering of old small- and micro-hydro plants have pervasively emerged worldwide. Hydropower production from reservoirs involves medium- and large-scale hydropower plants/stations that may interrupt the continuity of river flow. Small-hydropower plants (SHPs), in contrast, can be constructed directly in rivers or canals without building any new dams. SHPs are known to have conspicuous advantages that hydropower generation is technically mature, they are easy to install and maintain, and they have low operating and maintenance costs. The negligible environmental impact and comparatively low costs of SHPs offer an opportunity for clean energy conversion and management, either connecting power grid systems to urban areas or providing off-grid energy to remote rural areas [20,21]. Small-hydropower plants/turbines furnish over 13 million households with electricity in Europe, which avoids an emission of 29 million tons of CO_2 annually [22]. Today with the rising energy prices, SHPs could be a practical solution to rural electrification. Promoting the installation of SHPs annexed to existing water supply systems embodies the concept of sustainable development while meets present energy demands without endangering the capability of the next generations to fulfill their own demands.

A typical SHP refers to a power plant with its generating capacity less than 25 megawatts (MW) in China, less than 15 MW in India, and less than 10 MW specified by the European Small Hydropower Association [23,24]. SHPs can be adapted to a variety of water-related infrastructures [25], and such adaptation creates a great opportunity to boost renewable and clean energy production [26,27]. A water supply

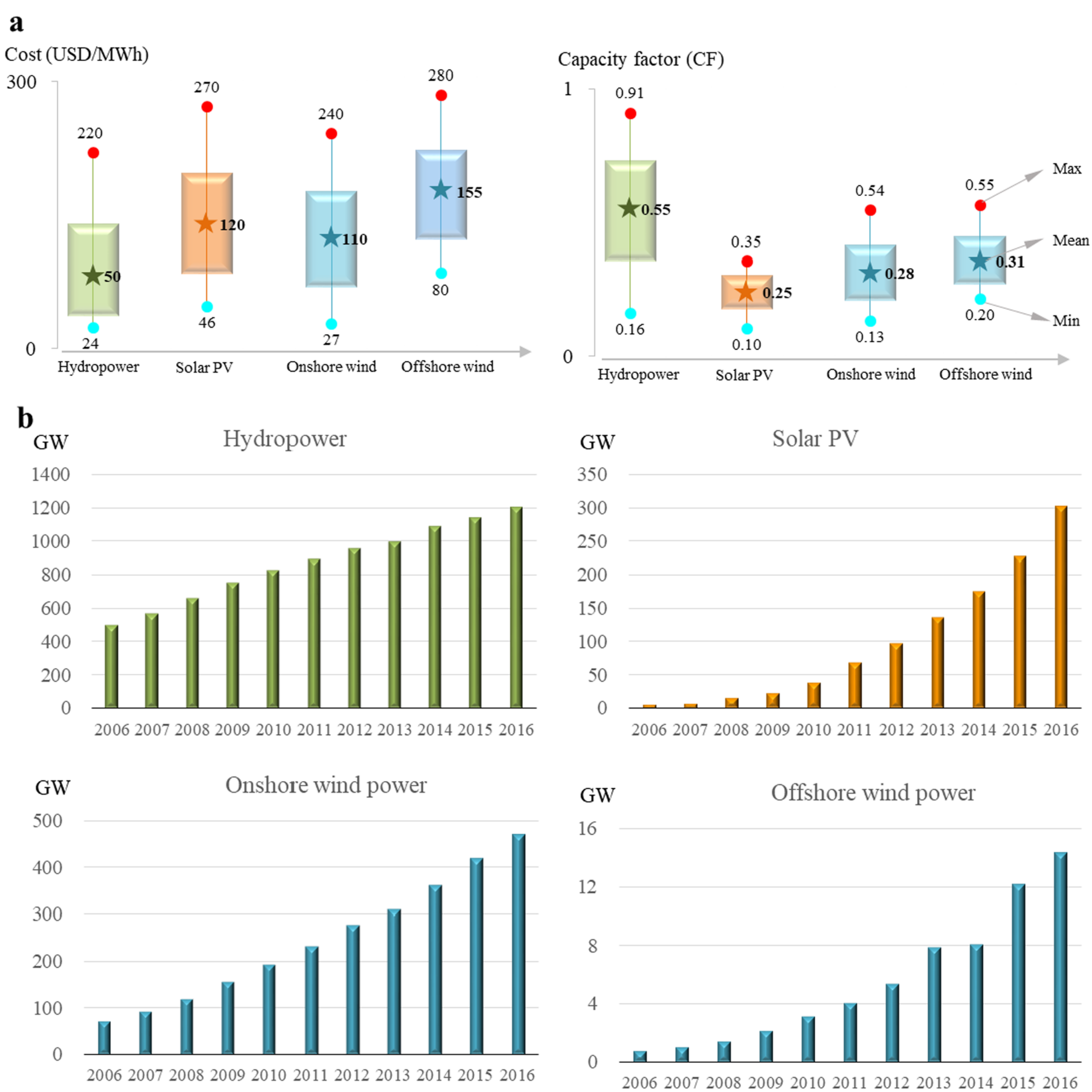

Fig. 1. Uncertainty in power generation cost and capacity factor (CF) of four dominant renewable energy sources (i.e., hydropower, solar PV power, onshore wind power and offshore wind power) as well as their global annual capacity (Gigawatts, GW) (2006–2016). a. Uncertainty of power generation cost and CF. b. Annual capacity. Notes: the data tracked 155 countries including Africa, Asia, Central America, the Caribbean, Eurasia, Europe, Middle East, North America, Oceania, South America, China, India and the United States, covering 96% of global GDP and representing 96% of global population. (Extracted from the *REN21 Renewables Global Status Report (2017)*).

system composed of rivers, canals and/or pipelines located ahead of water (treatment) facilities is perfectly suitable for installing small-hydropower turbines, yet neither reducing water supply to demanding sectors nor imposing serious impacts on ecosystems [28,29]. A number of researches focused on renewables integration by means of hydropower (including SHP) [30,31], hybrid power [32,33], which were closely associated with water sectors [34,35] to lift the synergies of the water-energy nexus. The Global Status Report of renewable energy (2017) [36] indicated that, owing to the comprehensive consideration of the uncertainty of renewable energy development techniques in different countries (Fig. 1), the advantages of small-hydropower over the other renewable energy sources are that small-hydropower has a lower mean power generation cost (mean cost = 50 USD/MWh) than solar photovoltaic (PV) power (mean cost = 120 USD/MWh), onshore wind power (mean cost = 110 USD/MWh) and offshore wind power (mean cost = 155 USD/MWh); and a higher mean capacity factor (mean CF = 0.55) than solar PV power (mean CF = 0.25), onshore wind power (mean CF = 0.28) and offshore wind power (mean CF = 0.31). In virtue of these advantages, SHPs have already been widely implemented worldwide for cleaner energy production, but not in Taiwan. Therefore, the holistic joint optimization of multi-sectoral water allocation and small-hydropower installation would serve as a viable approach to leveraging the synergistic benefits of the WFE Nexus at their optima [37,38], and resultantly provide stakeholders and policymakers with an innovative insight into the construction of transport and exchange mechanisms needed to manage WFE nutrients from sources to urban centers effectively [39,40].

The innovative nature of this study lies on the integration of existing water supply systems and small-hydropower installation by means of AI techniques as well as its application for the first time to stimulate the synergistic benefits of the WFE Nexus. The exploration was placed on three main foci. Firstly, the optimal cross-sectoral water allocation scheme was obtained from the trade-off between water supply reliability and the ratio of water storage to reservoir capacity using multi-objective optimization techniques. Secondly, the optimal small-hydropower installations under different water supply scenarios were acquired using evolutionary optimization techniques. Finally, the synergistic benefits of the WFE Nexus at their optima were achieved upon the optimal water allocation in alliance with the optimal small-hydropower installation (output) carried out in year-round and multi-year perspectives, respectively. The Shihmen Reservoir and its water supply system serving public and agricultural sectors of the Taoyuan City in northern Taiwan constituted the study case.

2. Study area and materials

The Shihmen Reservoir located in northern Taiwan is the pivotal multi-purpose reservoir for the Taipei metropolitan area. Its effective storage capacity and watershed area occupies 201 million m^3 and 763 km^2, respectively. The normal maximum water level of its conservation pool is 245 m, and the inactive water level of the dam stays at 195 m. The mainstream in this watershed is the Tamsui River, which has a length of 159 km and a drainage area of 2726 km^2. Fig. 2 presents the distribution diagram of the water supply system in the Shihmen Reservoir Watershed. The water distribution area embraces the Dahan River Basin and its tributary basins, where the Shihmen and Taoyuan irrigation areas spread over 121 km^2 and 270 km^2, respectively. The average annual rainfall in this watershed approximates 2500 mm, and flood seasons in general last from July to September. This multi-purpose reservoir has been managed to meet water demands of public and agricultural sectors, enable hydropower generation, and carry out flood control operation. The reservoir accommodates six floodgates (total maximum discharge equals 11,400 m^3/s) and two tunnel spillways (total maximum discharge equals 2400 m^3/s) [17]. Two hydropower plants were installed in the reservoir, with total installed capacity, annual hydropower output and maximum discharge reaching 90 megawatts (= 2 * 45 MW), 230 million kWh and 137.2 m^3/s (= 2 * 68.6 m^3/s), respectively.

The Shihmen Reservoir routinely regulates water supply to demanding sectors. For instance, water released from the reservoir through the Shihmen Canal serves the needs of the public (domestic and industrial) and irrigation sectors in South Taoyuan while water is also released from the reservoir to the Shihmen Hydropower Station, the Houchih Weir, and the other weirs sequentially (Fig. 2). Surplus water will be released directly from reservoir spillways to the Houchih Weir if the public and irrigation water demands in areas other than South Taoyuan exceed the maximum discharge capacity (137.2 m^3/s) of the

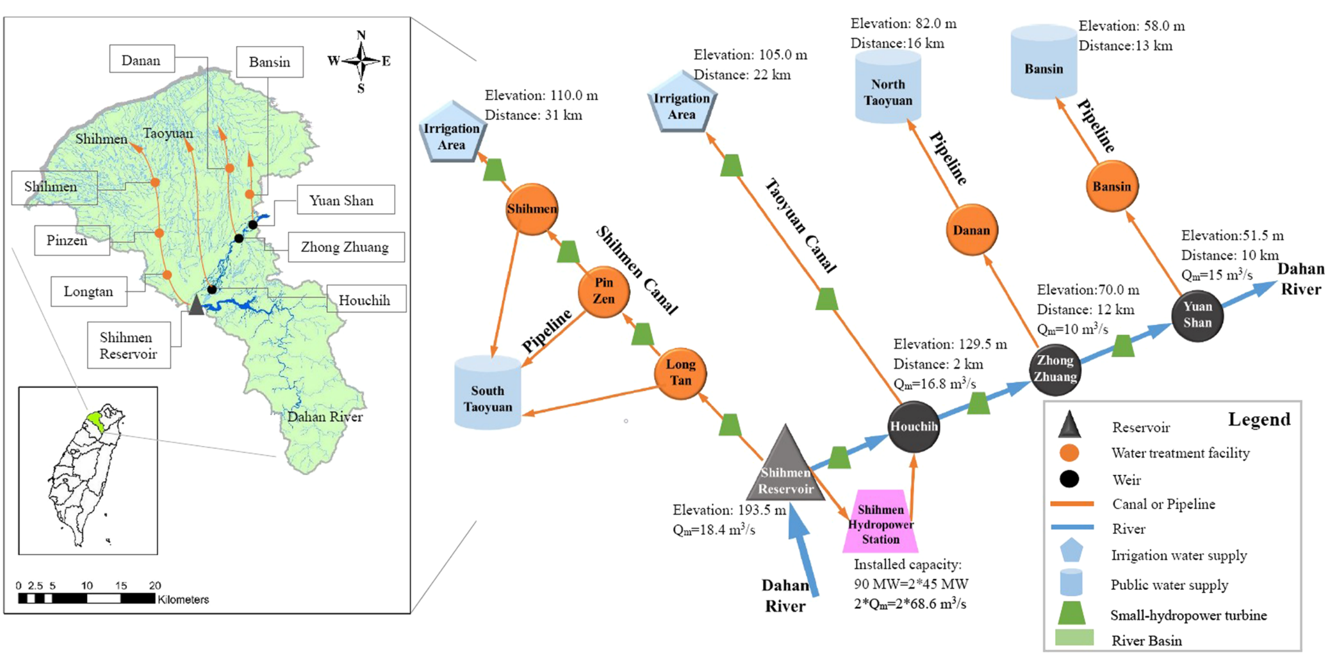

Fig. 2. Distribution diagram of the water supply system in the Shihmen Reservoir Watershed and the potential installation locations of small-hydropower turbines in the study area. Q_m is the maximal water supply/flow of the hydraulic project. Distance denotes the distance from the water supply source to the water demanding area. The water in canals and rivers is driven by gravity, while the water moving through pipelines is driven by pumps.

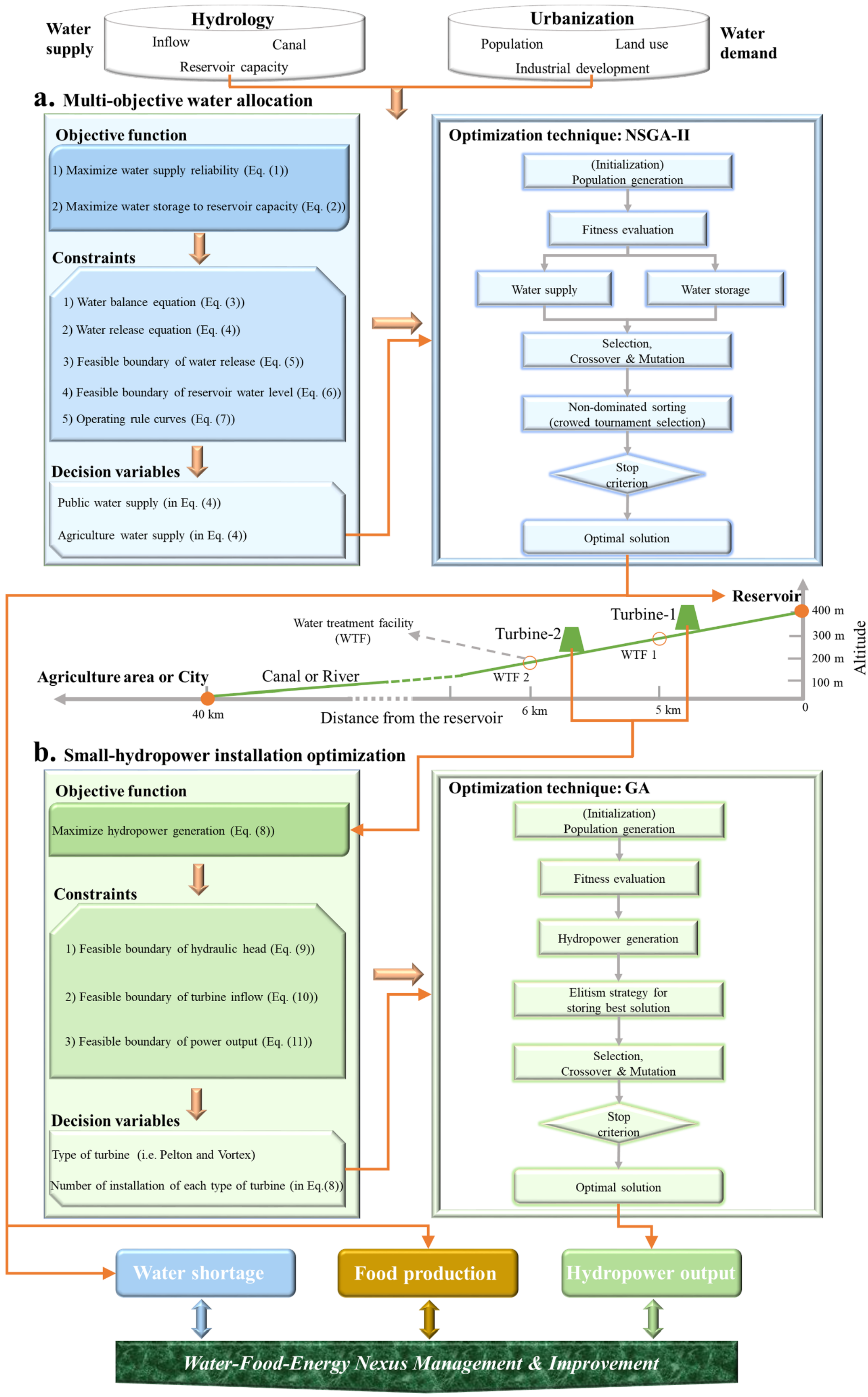

Fig. 3. Framework of Water-Food-Energy Nexus Management. a. NSGA-II-based water allocation optimization. b. GA-based small-hydropower installation optimization.

Shihmen Hydropower Station.

The Shihmen Reservoir authority has implemented M-5 rule curves to make tradeoffs in water supply between public and irrigation sectors [17], described as follows.

(a) The water allocation system will fully meet water demands if reservoir storage capacity exceeds the lower limit curve. That means the ratio (θ_{IR}) of water released to irrigation sectors equals 1, similarly for the public sectors ($\theta_{PUB} = 1$);
(b) θ_{IR} and θ_{PUB} are set as 0.75 and 0.9, respectively, if reservoir storage falls between the lower limit curve and the critical lower limit curve; and
(c) θ_{IR} and θ_{PUB} are set as 0.5 and 0.8, respectively, if reservoir storage falls below the critical lower limit curve.

SHPs drive impulse or reaction turbines to produce hydroelectricity with little or no water stored. Small-hydropower thus offers a unique insight into the improvement of water use efficiency [24,41]. The potential installation locations of small-hydropower turbines in this study are shown in Fig. 2. In addition, the architectures and characteristics of two typical types of turbines (Pelton and Vortex) recommended for small-hydropower generation can be found in [25,42]. Pelton turbines are usually implemented under the conditions of hydraulic heads exceeding 40 m and water flow less than 0.02 m^3/s, where the installed capacity per unit would reach 6 kW [25,42] (https://www.youtube.com/watch?v=XrxT2BG6V9I). Vortex turbines are capable of producing energy under the conditions of hydraulic heads less than 2 m and water flow less than 3 m^3/s, where the installed capacity of each unit would reach up to 30 kW [25] (https://www.youtube.com/watch?v=pXFkrKygXQY). Both Pelton and Vortex turbines were considered for installation in this study.

Given the water supply from the Shihmen Reservoir to the public and agricultural sectors, three hydrological scenarios with different annual operation durations of small-hydropower turbines (D) were designed to assess the hydropower installation scheme as well as the impacts of D on the output of small-hydropower turbines. Data for use in this study consisted of a total of 504 reservoir inflow datasets collected in 14 hydrological years (July-the next June 2002–2016) at a temporal scale of ten days (i.e. 36 ten-day periods * 14 years) and the average water demands of two recent hydrological years (i.e. 2015 and 2016). The reservoir characteristics and inflow data adopted in this study can be extracted from the Water Resources Agency in Taiwan (https://www.wra.gov.tw/, in Chinese).

3. Methods

The kernel methodology involved two parts: multi-sectoral water allocation optimization, and small-hydropower installation (output) optimization. For multi-objective reservoir operation subject to limited storage capacity under highly uncertain hydrological circumstances, it is a complicated and challenging task to methodically consider both water allocation reliability and WFE Nexus synergies. The AI-based optimization framework of multi-sectoral water allocation and small-hydropower installation is shown in Fig. 3. First, water allocation to public and agricultural sectors was optimized using the Non-dominated Sorting Genetic Algorithm (NSGA-II) based on 14-year reservoir inflows at a ten-day scale. Then small-hydropower installation (output) was optimized using the Genetic Algorithm (GA), utilizing the optimal water allocation results as the inflows (inputs) in the GA model. Ultimately, the synergistic benefits of the WFE Next under different hydrological scenarios were driven by the combination of the optimal outcomes of multi-sectoral water allocation and the output of small-hydropower turbines. The historical reservoir operation based on the M-5 rule curves was used as a benchmark. The main methods used in this study are introduced as follows.

3.1. Optimization of multi-sectoral water allocation using the NSGA-II

3.1.1. Multi-objective optimization model

To mitigate water shortages meanwhile increase the resilience of the water allocation system, water supply reliability (i.e. 1 – the water shortage index (WSI)) and the ratio of water storage to reservoir capacity (RWS) constituted the two objective functions of multi-purpose reservoir operation in this study. It is noted that the optimal solutions are closely linked with decision variables, i.e. water releases from the reservoir to different demanding sectors. This model (Fig. 3(a)) was formulated as follows.

Objective 1: maximize water supply reliability

$$\text{Maximize}(1 - \text{WSI}) = 1 - \frac{100}{\text{N}} \sum_{t=1}^{\text{N}} \left(\frac{\text{ST(t)}}{\text{DT}(t)}\right)^2 (\equiv \text{Minimize WSI}) \tag{1}$$

where ST(t) and DT(t) is the total water shortage and the total water demand in the t-th ten-day period, respectively. N is the number of ten-day periods investigated.

Objective 2: maximize the ratio of water storage to reservoir capacity (RWS)

$$\text{Maximize RWS} = \frac{1}{\text{N}} \sum_{t=1}^{\text{N}} \left(\frac{\text{S(t)}}{\text{V}}\right) \tag{2}$$

where S(t) is the reservoir storage in the t-th ten-day period. V is the maximum reservoir capacity.

Constraints: reservoir operation should obey physical constraints including the water balance equation (Eq. (3)), the water release equation (Eq. (4)), the feasible boundaries of water release and the reservoir water level (Eqs. (5) & (6)), and reservoir operation rules (Eqs. (7a) & (7b)). The mathematical formulations of these constraints were given as follows.

$$S(t+1) = S(t) + (I(t) - R_{total}(t))\cdot\Delta t \tag{3}$$

$$R_{total}(t) = R_{IR}(t) + R_{PUB}(t) + R_{ECO}(t) + R_{SP}(t) \tag{4}$$

$$R_{min} \le R_{total}(t) \le R_{max} \tag{5}$$

$$S_{min} \le S(t) \le S_{max} \tag{6}$$

$$R_{IR}(t) = D_{IR}(t)\cdot\theta_{IR} \tag{7a}$$

$$R_{PUB}(t) = D_{PUB}(t)\cdot\theta_{PUB} \tag{7b}$$

where $S(t)$ and $I(t)$ are the storage and inflow of the reservoir in the t-th ten-day period, respectively. $R_{IR}(t)$, $R_{PUB}(t)$, $R_{ECO}(t)$, $R_{SP}(t)$ and $R_{total}(t)$ are the water release for irrigation, public sectors, satisfying basic eco-flow of the river, through the spillway, and the total water release in the t-th ten-day period, respectively. Δt is the time step. R_{min} and R_{max} are the minimal and maximal water release, respectively. S_{min} and S_{max} are the minimal and maximal storage of the reservoir, respectively. $D_{IR}(t)$ and $D_{PUB}(t)$ are the water demands of irrigation and public sectors in the t-th ten-day period, respectively. θ_{IR} and θ_{PUB} are the ratios of water releasing to irrigation and public sectors, respectively, which will be determined by reservoir operation rules. The analyses of this study were grounded on the long-term observed data sets (inflow and storage only) obtained from our Water Resources Agency, where evaporation and precipitation was not explicitly computed in the mass balance equation, Eq. (3), because these values were either relatively small or transformed into the inflow and/or storage of the reservoir.

3.1.2. Non-dominated sorting genetic algorithm-II (NSGA-II)

In this study, the NSGA-II was applied to searching the optimal reservoir operations that maximized both water supply reliability and the RWS during 2002 and 2016. The NSGA-II is an evolutionary algorithm firstly proposed by Deb [43] and is commonly used in the optimization of multi-objective problems in various engineering fields [44], for instance, reservoir operation [45,46], water allocation [47,48], water resources management [49,50]. In this study, the NSGA-II was implemented following the procedure shown in Fig. 3(a), addressed below.

Step 1: Initialize a population P_0 of size N_{pop} randomly and evaluate their fitness values; implement the fast non-dominated sorting to partition the population into different ranks; and calculate the crowing distances of the population. Real-coded solutions for the decision variables (water releases) are used.

Step 2: Perform the crowed tournament selection operator to choose chromosomes with a higher fitness value (i.e. elitism preserving strategy) for producing the offspring of the next generation in the gene pool; perform the crossover operator with probability (P_c) to re-combine two parent chromosomes into new offspring chromosomes; and perform mutation operator with probability (P_m) for maintaining genetic diversity in the population. The three operators are used to generate an offspring population Q_0 of size N_{pop}.

Step 3: For the k-th generation, evaluate the fitness values of Q_k; combine Q_{k-1} and Q_k into an intermediate population P_k of size $2N_{pop}$; implement the fast non-dominated sorting to partition this combined population into different ranks; and calculate the crowding distances of the population.

Step 4: Select a new parent population P_{k+1} of size N_{pop} from P_k using the crowed tournament selection; generate an offspring population Q_{k+1} through crossover and mutation operators; and evaluate their fitness values.

Step 5: Terminate the computation according to stop criteria by evaluating the solutions through Steps 2–4. If the generation number is less than the maximal generation (G_{max}), then repeat Steps 2–5. Otherwise, stop iteration and output the optimal results.

The NSGA-II model for water allocation optimization was driven by a total of 504 datasets (=1 reservoir * 36 ten-day periods * 14 years), 1008 (=504 * 2) decision variables and 2016 (=504 * 4) constraints (referred to Fig. 3(a)). The population size (N_{pop}), the number of the maximal generation (G_{max}), the crossover probability (P_c) and the mutation probability (P_m) were set as 1000, 500, 0.9 and 0.1, respectively. It was noticed that the parameters of the NSGA-II could be obtained using an intensive trial-and-error procedure for producing converged results.

3.2. Optimization of small-hydropower installation using the GA

3.2.1. Small-hydropower installation optimization model

Incorporation of small-hydropower plants/turbines into water supply networks has gained more and more attention in the planning and management of green urban development all over the world [51,52]. It is now in the context to increase cleaner energy generation to reduce greenhouse gas emission [53]. Table 1 shows the power generation profile and power generation cost in Taiwan, which implies there is much room to promote hydropower generation for expanding its market share in response to sustainable development.

Water allocation systems convey water mostly from high-elevation reservoirs to residential areas. A water treatment facility (WTF) takes control of water pressure resulting from elevation difference along the canal/river (in Figs. 2 and 3). Installation of small-hydropower turbines between WTFs and reservoirs would create significant hydraulic heads that benefit power generation. Identifying the type and number of small-hydropower turbines enabled to maximize hydropower output was the mission of the small-hydropower installation optimization model. The hydraulic head (=total of available hydraulic heads − loss of hydraulic heads) acquired from the optimal combination of turbines and installation base was used to locate the potential installation of small-hydropower turbines [24,41]. The optimal solution was driven by decision variables, i.e. turbine inflow (=tailrace outflow) and the variables describing the types of turbines and the number of each type of turbines installed. To be more concise, the main functions of the small-hydropower installation optimization model were to maximize the overall output of all small-hydropower turbines suggested in the water supply system and to search out the optimal combination of the turbine type and the number of each turbine type (i.e. decision variables) at possible installation locations (i.e. canal or river). This model (Fig. 3(b)) was formulated as follows.

Objective function: maximizing the average annual output of small-hydropower turbines (ASHO)

$$\text{Maximize} \quad \text{ASHO} = \frac{1}{n}\sum_{i=1}^{K_j}\sum_{j=1}^{M}\sum_{t=1}^{N} P_{i,j}(t)\cdot D\cdot\alpha(t) \tag{8a}$$

$$P_{i,j}(t) = \eta\cdot\rho\cdot g\cdot Q_{i,j}(t)\cdot H_{i,j}(t) \tag{8b}$$

where $P_{i,j}(t)$ is the i-th power output at the type j small-hydropower turbines in the t-th ten-day period. K_j and M, i.e. decision variables, are the number of the type j small-hydropower turbines and the total number of small-hydropower turbine types, respectively (in our case, M = 2 types). N is the number of time steps (ten-day periods) in the whole operation time interval. n is the number of years in the whole operation time interval (in our case, n = 14 years). D is the annual operation duration of small-hydropower turbines (in our case, D of the three scenarios were set as 6000, 7000 and 8000 h, respectively. $\alpha(t)$ denotes the ratio of operation duration in the t-th ten-day period to D ($\sum_{t=1}^{N}\alpha(t) = D$), in connection with turbine inflow (i.e. water supply to public and agricultural sectors). η is the efficiency coefficient of the small-hydropower turbine. ρ is the density of water. g is the gravity acceleration. $Q_{i,j}(t)$ and $H_{i,j}(t)$ are the i-th turbine inflow and the i-th hydraulic head of the type j small-hydropower turbines in the t-th ten-day period, respectively. For long-term operation at a scale of ten-day period, the efficiency coefficient of the SHP in Equation (8b) was set as the mean capacity factor (0.55) revealed in [36] (referred to Fig. 1(a)), while under the situation of short-term operation at daily or hourly scales, it would need to consider the uncertainty in the capacity factor of the SHP that varied between 0.30 and 0.65 in general. In other words, the uncertainty in the capacity factor of the SHP was higher under short-term operation than under long-term operation.

From the perspective of planning for SHP installation, three scenarios corresponding to different annual operating hours (6000, 7000 and 8000 h) were established to evaluate the impacts of hydrological conditions (dry, normal and wet years) and annual operating hours on

Table 1
Power generation profile and power generation cost in Taiwan (2017).

Energy type	Installed capacity (10 MW)	Power output (10 MW)	Power generation cost (USD/MWh)
Coal	1840	1259	53.7
Liquefied natural gas (LNG)	1522	934	78.3
Fuel oil	307	128	148.0
Nuclear power	514	224	43.3
Pumped storage hydropower	260	33	116.7
Renewable energy			
Hydropower[a]	209	54	58.0
Solar power	177	17	260.0
Wind power	69	17	62.3
Biomass energy	10	2	–
Waste and landfill gas	63	33	–

Data sources:
1. *2017 annual report of national power supply and demand,* Bureau of Energy by Ministry of Economic Affairs, Taiwan.
2. https://www.taipower.com.tw/tc/page.aspx?mid=196 (exchange rate @ 30).
[a] Purchase price: 66.67 USD/MWh.

SHP output, respectively.

Constraints: small-hydropower generation should obey physical constraints including the feasible boundaries of hydraulic heads (Eqs. (9a) and (9b)), turbine inflow (Eqs. (10a) and (10b)) and power output (Eq. (11)). The mathematical formulations of these constraints were given as follows.

$$H_{min,j} \le H_{i,j}(t) \le H_{max,j} \tag{9a}$$

$$0 < \sum_{i=1}^{K_j} \sum_{j=1}^{M} H_{i,j}(t) \le (H_{total} - H_{loss}) \tag{9b}$$

$$0 < Q_{i,j}(t) \le Q_{max,j} \tag{10a}$$

$$\sum_{i=1}^{K_j} \sum_{j=1}^{M} Q_{i,j}(t) \le (R_{IR}(t) + R_{PUB}(t)) \tag{10b}$$

$$0 < P_{i,j}(t) \le P_{max,j} \tag{11}$$

where H_{total} and H_{loss} are the total of available hydraulic heads and the loss of hydraulic heads, respectively. $H_{min,j}$ and $H_{max,j}$ are the minimal and maximal hydraulic heads of the type *j* small-hydropower turbines, respectively. $Q_{max,j}$ and are the maximal water flow and the maximal power output of the type *j* small-hydropower turbines, respectively. The total inflow of all small-hydropower turbines in each canal or river should not exceed the maximal water flow of the canal or the maximal water supply of weirs.

3.2.2. Genetic algorithm (GA)

In this study, the GA was implemented to optimize the output of small-hydropower generation during 2002 and 2016 at a ten-day scale. The inputs of the GA model were the inflows relevant to the optimal cross-sectoral water allocation results. The GA is a popular evolutionary algorithm commonly applied to single-objective optimization problems in various engineering fields [54,55], for instance, reservoir operation [56] and water resources management [57]. In this study, the small-hydropower installation optimization model was considered as a function of the optimal multi-sectoral water allocation, and the GA was then used to optimize the output of small-hydropower generation. The computational steps (Fig. 3(b)) of the GA are described below.

Step 1: Randomly create an initial population I_0 of size I_{pop}. Integer-coded and real-coded solutions were used for decision variables K_j and M as well as for the decision variable of turbine inflow, respectively. It is noted that the value of decision variable M varies between 0 and 2 (= total types of small-hydropower turbines, in Table 2 and Fig. 3) while the value of decision variable K_j varies between 0 and the maximal number of the type *j* small-hydropower turbines. Besides, the maximal number of each type of small-hydropower turbines could be obtained from the feasible boundary of hydraulic heads (Eq. (9)).
Step 2: Implement the tournament selection, the crossover operator with probability (p_c) and the mutation operator with probability (p_m) to produce an offspring population S_0 of size I_{pop}.
Step 3: Evaluate the fitness values of S_k for the *k*-th generation, merge S_{k-1} and S_k into an intermediate population I_k of size $2 * I_{pop}$, and divide this merged population into different ranks in terms of fitness values.
Step 4: Select a new parent population I_{k+1} of size I_{pop} from I_k using the tournament selection, produce an offspring population I_{i+1} through crossover and mutation operators, and evaluate their fitness values.
Step 5: Repeat Steps 3 and 4 if the generation number is less than the maximal generation (g_{max}). Otherwise, stop iteration and output the optimal results.

The GA model for SHP installation optimization was driven by a total of 1008 datasets (= (1 canal & 1 river) * 36 ten-day periods * 14 years), 2016 (= 1008 * 2) decision variables and 5040 (= 1008 * 5) constraints (referred to Fig. 3(b)). The population size (I_{pop}), the maximal generation (g_{max}), the crossover probability (p_c) and the mutation probability (p_m) were set as 500, 300, 0.8 and 0.1, respectively. It was noticed that the parameters of the GA could be obtained using an intensive trial-and-error procedure for producing converged results.

4. Results and discussion

This study was centered on probing into small-hydropower installation motivated by multi-sectoral water allocation to boost the synergistic benefits of the WFE Nexus with the use of AI-based heuristic techniques. Two types of hydrological years (i.e. wet and dry years) were selected to evaluate the improvement made by the proposed approach over the benchmark simulation in the synergistic benefits of the WFE Nexus. The study results and findings were drawn and discussed in details, as shown below.

4.1. Optimal multi-sectoral water allocation using the NSGA-II

To optimize multi-sectoral water allocation for water deficit mitigation, this study implemented the NSGA-II to search the optimal Pareto Front between water supply reliability (= 1 – WSI) and the RWS under three designed scenarios of reservoir inflow, i.e. wet year (2005), dry year (2011), and multi-year (2002–2016) at a ten-day scale, respectively. Fig. 4 showed a total of 1000 non-dominated solutions associated with the multi-year scenario, which converged at the 500th generation and were distributed independently along the Pareto Front across two objectives (RWS and 1-WSI). Solutions A and C represented the optimal operation exclusively considering water storage and water

Table 2
Results of water allocation obtained from M-5 rule curves simulation (benchmark) and NSGA-II optimization (Fig. 4) under three hydrological scenarios, respectively.

Solution	Indicator	Scenario		
		Wet year[d] (2005)	Dry year[e] (2011)	Multi-year[f] (2002–2016)
M-5 rule curves simulation result	WSI[a]	11	19	15
	RWS[b]	46	35	41
	AHO[c]	241	217	235
Solution A in NSGA-II	WSI	10 (9.1 [g])	17 (10.5)	13 (13.3)
	RWS	56 (21.7)	41 (17.1)	49 (19.5)
	AHO	246 (2.1)	222 (2.3)	242 (3.0)
Solution B in NSGA-II	WSI	9 (18.2)	14 (26.3)	11 (26.7)
	RWS	50 (8.7)	39 (11.4)	47 (14.6)
	AHO	250 (3.7)	225 (3.7)	246 (4.7)
Solution C in NSGA-II	WSI	8 (27.3)	11 (42.1)	9 (40.0)
	RWS	48 (4.3)	37 (5.7)	44 (7.3)
	AHO	257 (6.6)	228 (5.1)	252 (7.2)

[a] Average water shortage index (agricultural and public sectors) over ten-day periods during non-typhoon seasons (%).
[b] Average ratio of water storage to reservoir capacity (%).
[c] Average annual hydropower output (10^6 kWh) of the Shihmen Hydropower Station under the condition that no small-hydropower turbines were installed in the canals and rivers of the study area.
[d] Occurrence frequency of a wet year (2005 is the representative in this study) was 20% during 2002 and 2016. A hydrological year starts from July to the next June.
[e] Occurrence frequency of a dry year (2011 is the representative in this study) wa 80% during 2002 and 2016.
[f] Multi-year denotes the time series spanning from 2002 up to 2016 (14 years).
[g] Improvement rate (%), and M-5 rule curves simulation was the benchmark model.

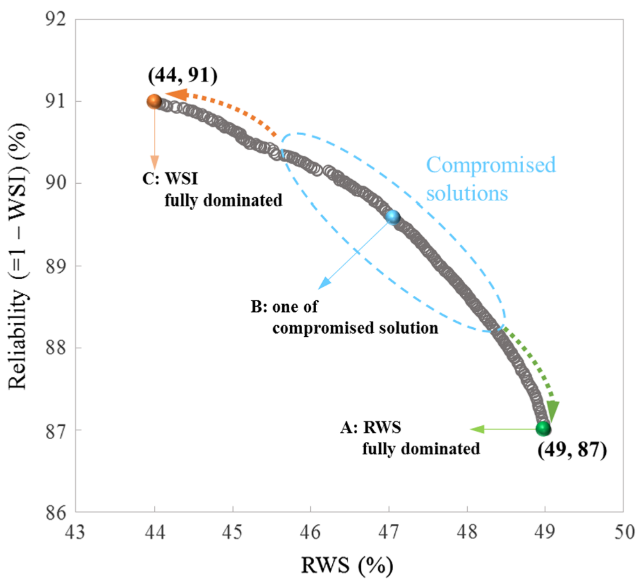

Fig. 4. Pareto Front of the NSGA-II with respect to the ratio of water storage to reservoir capacity (RWS) and water supply reliability (i.e. 1 – water shortage index (WSI)) based on reservoir inflow collected from 2002 up to 2016, which converged at the 500th generation.

supply reliability, respectively. The results indicated that the two objectives competed with each other, i.e. higher water supply reliability followed in the wake of a lower RWS, and vice versa. In other words, Solution A appeared to be the situation that the RWS was fully dominated whereas Solution C would be the situation that the reliability (1-WSI) was fully dominated. The remaining ones like Solution B were labeled as compromised solutions, which revealed tradeoffs made between the two objectives. With these optimal solutions on hand, decision makers could convincingly opt for the most adequate reservoir operation strategy in answer to the hydrological condition encountered for better managing the intense rivalry among water demanding sectors. For instance, the optimal solutions near Solution A tended to maximize the RWS, which suggested reservoir operation strategies pertinent to these optimal solutions would be suitable to implement in wet years. In contrast, the optimal solutions near Solution C were prone to maximizing water supply reliability, which implied reservoir operation strategies related to these optimal solutions would be suitable to implement in dry years. Alternatively, reservoir operation strategies associated with compromised solutions (e.g. Solution B) were considered suitable for normal years.

Table 2 presented the optimal water allocation obtained from the NSGA-II under the three designed hydrological scenarios. It was easy to observe that the NSGA-II produced much better performances (smaller WSI, larger RWS, and larger average annual hydropower output (AHO)) than the M-5 rule curves simulation for all the three scenarios. The results demonstrated that the optimal NSGA-II solutions could effectively mitigate water deficit, significantly increase reservoir storage, and raise hydropower output. Under the multi-year scenario, the compromised solution (Solution B) appeared to enhance the RWS and AHO by 14.6% and 4.7% accordingly while reduce the WSI (water shortage) by as much as 26.7%. It was an interesting finding that subject to the same water demands, the highest improvement rate in RWS (21.7%) was achieved by the RWS-oriented fully dominated solution (Solution A) under the wet year scenario, whereas the highest improvement rate in WSI (42.1%) was achieved by the WSI-oriented fully dominated solution (Solution C) under the dry year scenario. These phenomena were in line with the search directions of the NSGA-II. For instance, the obtainment of the RWS-oriented fully dominated solution (Solution A) was to conduct solution search in a direction toward maximizing the RWS while the obtainment of the WSI-oriented fully dominated solution (Solution C) was to conduct solution search in a direction toward minimizing the WSI (i.e. maximizing 1-WSI). Besides, the NSGA-II solutions could lift hydropower output with improvement rates ranging between 2.1% and 7.2% under all scenarios, which were obviously smaller than those of WSI and RWS. This could be a consequence of priority setting for reservoir operation, where water demands from public and irrigation sectors, rather than hydropower generation, always gained top priority.

Water shortages endangering public and agricultural sectors could be ameliorated through reservoir operation achieving the optimal tradeoff between water supply and reservoir storage. The diverse NSGA-II solutions could significantly improve the efficiency of traditional water supply regulated by M-5 rule curves. The improvement rate associated with water shortage (WSI) was higher than that of hydropower output in every case because public and irrigation water demands were granted higher priority in reservoir operation than hydropower generation.

4.2. Small-hydropower installation optimization using the GA

The model pursuing the optimal small-hydropower installation (output) was established using the GA upon four water allocation cases (i.e. M-5 rule curves simulation result, and Solutions A, B, and C obtained from the NSGA-II) in a multi-year perspective (14 hydrological years spanning between 2002 and 2016) at a temporal scale of ten days. Fig. 5 showed the results under the constraint that the annual operation duration (D) of small-hydropower turbines was set as 6000 h. The results relevant to the average annual output of small-hydropower turbines (ASHO) shown in Fig. 5(a) indicated that all the optimal solutions associated with the four cases converged before the 300th generation and the largest ASHO occurred in the case of Solution C. It could be speculated that Solution C would greatly mitigate the WSI by distributing more water from the reservoir to the public and agricultural sectors (= the available water volume for small-hydropower generation) and consequently the larger volume of water supply (inputs) would request for more installation of small-hydropower turbines, at the expense of convergence speed.

Fig. 5(b) and Table 3 outlined the GA results recommending the optimal numbers and locations of small-hydropower turbines to be installed, where the M-5 rule curves simulation served as the benchmark. Taking the case of Solution C for example, suggestions were made on the installations of turbines: 39 Pelton + 4 Vortex turbines in the Shihmen Canal, 4 Vortex turbine in the Taoyuan Canal, and 43 Pelton + 5 Vortex turbines in the Dahan River. The total installed capacity turned out to be 882 kW, and therefore shed light on an ASHO of 3.70×10^6 kWh, with an improvement rate exceeding 27% as D = 6000 h (Table 3). It was also interesting to learn that the ASHO significantly and non-linearly increased with the annual operation duration of small-hydropower turbines. There would be two reasons for engendering such a non-linear phenomenon. First, in technical aspects and Eq. (8), small-hydropower generation relied not only upon annual operation duration (D) but also upon the ratio of operation duration in every time step t to D (i.e. $\alpha(t)$) while $\alpha(t)$ had a sophisticated non-linear relationship with turbine inflow (i.e. water supply to public and agricultural sectors). Second, the GA would generate a non-linear mapping from annual operation duration onto hydropower output. As for the applicability of the GA model with different annual operation durations (D) of small-hydropower turbines, the results suggested that the achievable operating hours in dry years would be 6000 h whereas there is room to extend operating hours to 7000 h in normal years and to 8000 h in wet years.

Another important finding was that the total number of turbines recommended for the Shihmen Canal increased with water supply amount, i.e. the largest number of installation was derived from Solution C. Similar situation occurred for the Dahan River. An explanation was that larger water supply (Solution C) from the reservoir

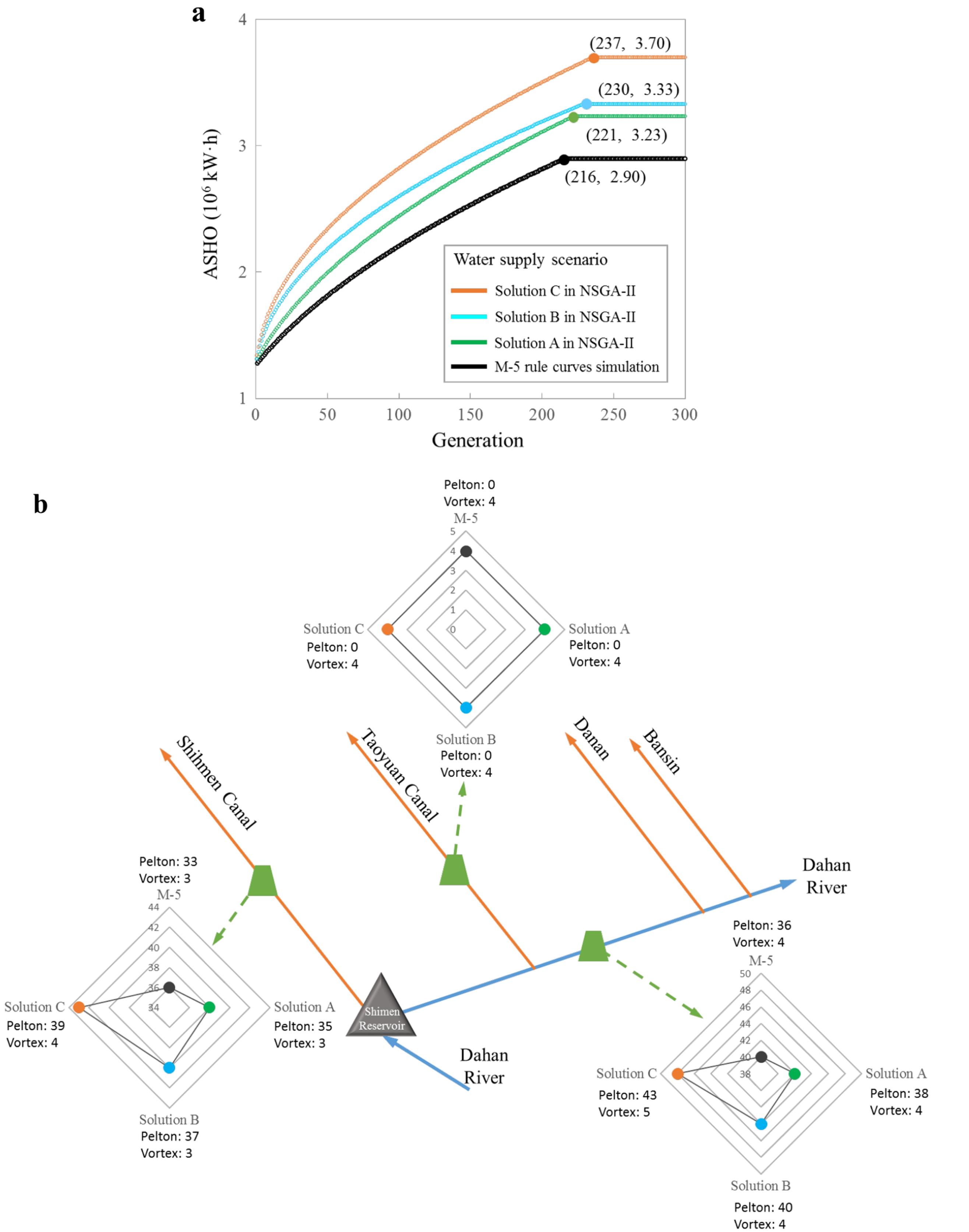

Fig. 5. Results of small-hydropower installation optimization. a. Optimal GA solutions that maximized the ASHO under the best water allocation solutions: A (RWS-oriented fully dominated solution); B (compromised solution); and C (WSI-oriented fully dominated solution) obtained from the NSGA-II, where the annual operation duration of small-hydropower turbines (D) was 6000 h and the GA solutions converged before the 300th generation. b. Optimal installation of small-hydropower turbines in the water supply system under the four scenarios of water supply (i.e., M-5 rule curves simulation result, and Solutions A–C) ASHO denotes the average annual output (10^6 kWh) of small-hydropower turbines RWS denotes the ratio of water storage to reservoir capacity. WSI denotes the water shortage index.

Table 3

Results of small-hydropower installation (output) optimized by the GA in response to water allocation scenarios of the M-5 rule curves simulation (benchmark) and NSGA-II optimization (Fig. 4) during 2002 and 2016 (14 years), respectively.

Solution	Turbine type	Number of small-hydropower turbines installed			Total installed capacity (kW)	ASHO[a] (10^6 kWh)		
		In Shihmen Canal (83.5m[b])	In Taoyuan Canal (24.5 m)	In Dahan River (64.0 m)		6000 h[c]	7000 h	8000 h
M-5 rule curves simulation result	Pelton Vortex	33 3	0 4	36 4	744	2.90	3.55	4.14
Solution A (RWS fully dominates) in NSGA-II	Pelton Vortex	35 3	0 4	38 4	768	3.23 (10.0[d])	3.88 (9.3)	4.48 (8.3)
Solution B (compromised) in NSGA-II	Pelton Vortex	37 3	0 4	40 4	792	3.33 (14.6)	4.27 (20.3)	4.88 (18.0)
Solution C (WSI fully dominates) in NSGA-II	Pelton Vortex	39 4	0 4	43 5	882	3.70 (27.7)	4.66 (31.2)	5.23 (26.4)

[a] Average annual output (10^6 kWh) of small-hydropower turbines.
[b] Available hydraulic head.
[c] Annual operation duration (hours) of small-hydropower turbines.
[d] Improvement rate (%), and M-5 rule curves simulation was the benchmark model.

to demanding sectors would increase the water volume available to small-hydropower generation and therefore led to a larger installed capacity of turbines. Regarding installation locations, the Shihmen Canal and the Dahan River were found very suitable to install both types of turbines, while the Taoyuan Canal was considered suitable to install Vortex turbines only. Available hydraulic heads for turbine installation interpreted such situations. Bearing in mind Pelton turbines required hydraulic heads exceeding 40 m, Fig. 2 revealed that the

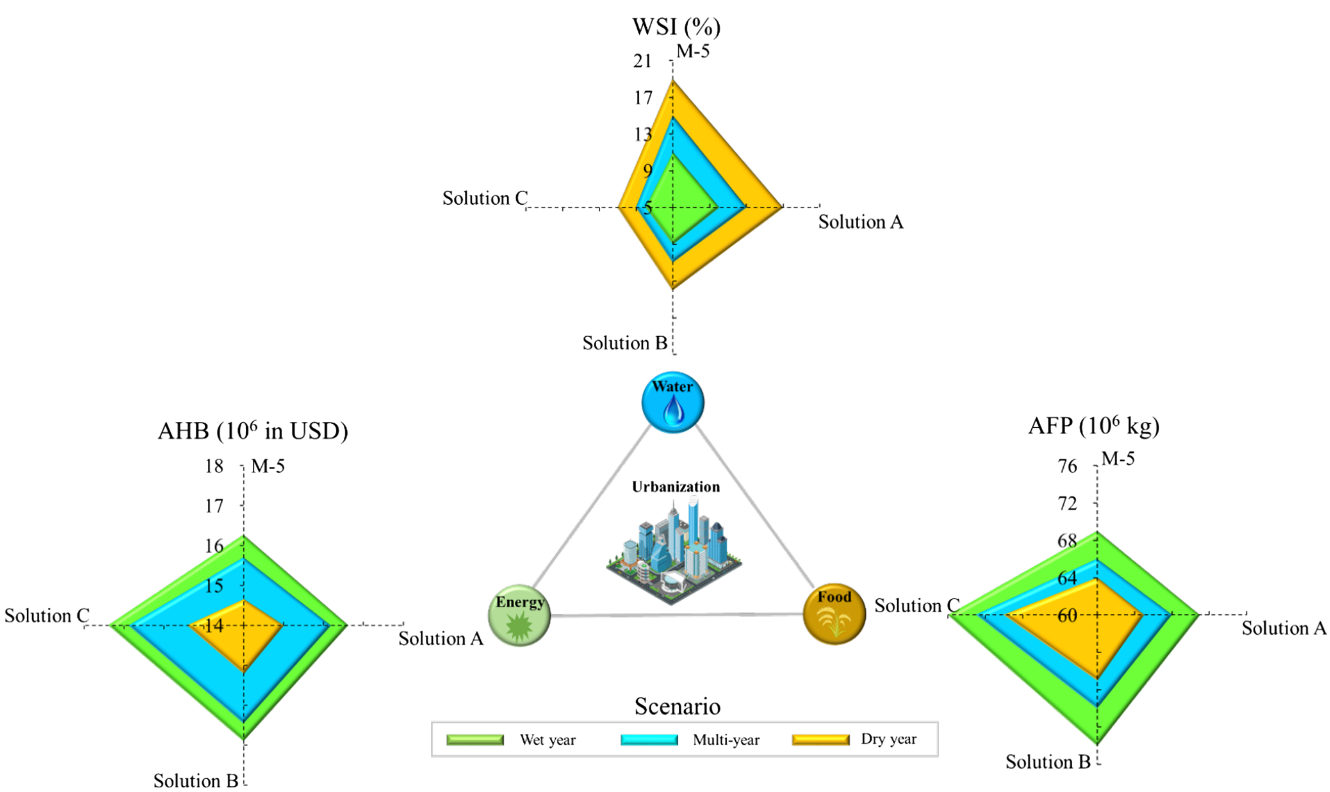

Fig. 6. Benefits of the Water-Food-Energy Nexus based upon the collaborative optimal results obtained from water allocation optimization (NSGA-II) and small-hydropower output optimization (GA) under three hydrological scenarios, where results of NSGA-II optimization were in comparison with those of M-5 rule curves simulation.
Scenario setting:
Multi-year: time series spanning from 2002 up to 2016 (14 years).
Wet year (2005 is the representative in this study): occurrence frequency of a wet year was 20% during 2002 and 2016.
Dry year (2011 is the representative in this study): occurrence frequency of a dry year was 80% during 2002 and 2016.
Hydrological year: starting from July to the next June in the study area.
Indicators of benefits:
WSI (%): average water shortage index (for agricultural and public sectors) over ten-day periods during non-typhoon seasons.
AHB (10^6 in USD): average annual hydropower benefits of the Shihmen Hydropower Station and small-hydropower turbines.
AFP (10^6 kg): average annual food production (including rice, vegetables and fruits).

hydraulic head requirement of Pelton turbines could be satisfied in the Shihmen Canal (available hydraulic head = 83.5 m = 193.5–110 m) as well as in the Dahan River (available hydraulic head between the reservoir and the Houchi Weir = 64 m = 193.5–129.5 m) but could not be met in the Taoyuan Canal (available hydraulic head = 24.5 m = 129.5–105 m). Therefore, the GA results claimed that the number of turbines to be installed was dominated mainly by the available water volume while the potential locations to install small-hydropower turbines were dominated mainly by the available hydraulic head. This further explained why the Shihmen Canal had the largest available hydraulic head but there were lesser turbines to be installed here (Table 3).

At the planning phase of SHP installation explored in this study, special attention was paid to the optimization search of the type and the number of SHP turbines (i.e. two decision variables) that could be installed in the existing water supply system by investigating available water volumes and water heads. The optimal results indicated that 74 Pelton and 11 Vortex turbines could be installed under the RWS-oriented fully dominated solution while 82 Pelton and 13 Vortex turbines could be installed under the WSI-oriented fully dominated solution (Fig. 5 and Table 3). While at the designing phase of SHP installation, it requires the identification of the potential locations of SHP turbines in combination with the in-situ geological survey and facility construction drawings in the study area.

In view of the Global Status Report of renewable energy (2017) [36] and recent economic cost analysis of SHP installation [28,29], it is manifest that one of the advantages making small-hydropower superior to the other renewable energy sources is that small-hydropower has a lower installed cost (mean installed cost = 600 USD/kW) than conventional hydropower (mean installed cost = 1900 USD/kW) excluding SHP and pumped storage hydropower, solar PV power (mean installed cost = 2000 USD/kW), onshore wind power (mean installed cost = 1800 USD/kW) and offshore wind power (mean installed cost = 3500 USD/kW). As known, the cost of energy from renewable energy sources is very strongly site dependent. Therefore the cost-benefit analysis of small-hydropower in this study adopted the mean installed cost mentioned above. Taking the WSI-oriented fully dominated solution (Solution C) for example, it was recommended to install 82 Pelton turbines with total installed capacity of 492 kW (= 82 * 6 kW) and 13 Vortex turbines with total installed capacity of 390 kW (= 13 * 30 kW) in the existing water supply system. This will bring a total installed cost of 529 thousand USD (= (492 + 390) * 600 USD) while lead to an average annual hydropower benefit ranging between 247 thousand USD (= 3700 MWh * 66.67 USD/MWh) and 349 thousand USD (= 5230 MWh * 66.67 USD/MWh) (Table 3). For this scenario based on current energy price structures, the SHP installed costs could be recovered in two or three years after the commencement of energy production.

In brief, there is a great potential for increasing hydropower output without endangering the water supply to public and agriculture sectors in all the cases (i.e. wet year, dry year and multi-year scenarios) if the proposed methodology that integrates small-hydropower turbines into the existing water supply system can be implemented. It was noted that the optimal values obtained in this study were only valid for the presented case in consideration of two turbine types (Pelton turbine with 6 kW installed capacity and Vortex turbine with 30 kW installed capacity), and there might be other combinations of turbines with different installed capacities that might yield similar results. It was also noted that the complexity of the NSGA-II model for water allocation optimization was closely linked with two objective functions as well as a total of 504 datasets, 1008 decision variables and 2016 constraints. It took about 30 min and 6 h for the NSGA-II to produce the converged results corresponding to scenarios based on one-year data and 14-year data, respectively. As for the GA applied to SHP installation optimization, its model complexity was closely linked with one objective function as well as a total of 1008 datasets, 2016 decision variables and 5040 constraints. It took about 20 min and 4 h for the GA to produce the converged results associated with scenarios based on one-year data and 14-year data, respectively. The computation was conducted by a DELL computer (Intel® Core™ i5, 7th Generation CPU @ 2.50 GHz, RAM 8 GB and 1 TB Hard Disk).

4.3. WFE Nexus benefits analysis

To assess the synergistic benefits of the WFE Nexus, the multi-sectoral water allocation optimization scheme was harmonized with the small-hydropower installation optimization scheme. Fig. 6 presented the synergistic benefits of the WFE Nexus based on the optimal water allocation (NSGA-II) and the optimal small-hydropower installation (GA) under the three designed hydrological scenarios (wet year, dry year, multi-year), where M-5 rule curves simulation was the benchmark. The synergistic benefits of the WFE Nexus in relation to Solution C (WSI fully dominated) demonstrated to boost greatly in all cases. For instance, the cases upon Solution C under the dry-year scenario (yellow color in Fig. 6) would generate the largest nexus benefits (WSI = 11% for the water sector, AFP = 70×10^6 kg for the food sector, and AHB = 15.42×10^6 in USD for the energy sector). It was easy to tell that the benefits associated with the four solutions could be ranked as: Solution C > Solution B > Solution A > M-5. This was grounded on the satisfaction degree of water demands, i.e. higher satisfaction degree (smaller WSI) would lead to higher AFP and AHB. It was also notable that a significant disparity in the synergistic benefits of the WFE Nexus was created among the three hydrological scenarios. As expected, the synergistic benefits of the WFE Nexus were higher in the wet year than in the dry year. This again supported the importance of water availability in contribution to the synergies of the WFE Nexus.

The reliability and effectiveness of the proposed methodology were next investigated. Table 4 summarized the improvement rates with respect to the synergistic benefits of the WFE Nexus obtained from the optimal results coupling multi-sectoral water allocation with small-hydropower installation under the hydrological scenarios, where M-5 rule curves simulation was the benchmark. The results of the WSI-oriented fully dominated solution (Solution C) pointed out that: the improvement rates of water deficit achieved 27.3% in the wet year and 42.1% in the dry year, respectively (Table 4), the improvement rates in the food sector were 10.1% in the wet year and 9.4% in the dry year, respectively (Table 4), and the hydropower benefits were 17.39×10^6 in USD in the wet year and 15.42×10^6 in USD in the dry year, respectively (Fig. 6), with improvement rates of 6.9% and 5.2%, respectively (Table 4). This revealed that Solution C would significantly mitigate water shortage in the dry year, rather than in the wet year. By contrast, Solution C would increase food production and hydropower output in the wet year, rather than in the dry year. This again disclosed the importance of water availability in expanding the synergies of the WFE Nexus. Moreover, the results of Solution C showed that the multi-year joint optimization under the collaboration of water allocation and small-hydropower installation could mitigate the average annual water shortage index (water sector) by up to 40%, raise the average annual food production (food sector) by as high as 10.6%, and drive up the average annual hydropower benefit (energy sector) by 17.05 million USD (purchase price: 66.67 USD/MWh), respectively. Such achievements were owing to less agricultural water shortage under this scenario.

In summary, the proposed methodology that pursuing the small-hydropower installation settled upon the optimal multi-sectoral water allocation demonstrated to significantly stimulate the synergistic benefits of the WFE Nexus, in comparison with those of the M-5 rule curves simulation. Besides, as compared to previous studies on the WFE Nexus such as the supply chain analysis [8,9], the life cycle assessment [11] and system dynamic simulation [12,13], the main findings of this study were in the best interests of the goals to make the Earth a better place to live and promote the environment as well as WFE sources into

Table 4
Improvement rates with respective to the benefits of the WFE Nexus obtained from the optimal results coupling multi-sectoral water allocation (NSGA-II, Fig. 4) with small-hydropower installation (GA) under three hydrological scenarios, respectively, where M-5 rule curves simulation was the benchmark model.

Solution	Nexus	Indicator	Scenario		
			Wet year[d] (2005)	Dry year[e] (2011)	Multi-year[f] (2002–2016)
Solution A (RWS fully dominates) in NSGA-II	Water	WSI[a]	9.1 [g]	10.5	13.3
	Food	AFP[b]	2.9	1.6	3.0
	Energy	AHB[c]	2.2	2.4	3.1
Solution B (compromised) in NSGA-II	Water	WSI	18.2	26.3	20.0
	Food	AFP	7.2	4.7	6.1
	Energy	AHB	3.9	3.8	4.8
Solution C (WSI fully dominates) in NSGA-II	Water	WSI	27.3	42.1	40.0
	Food	AFP	10.1	9.4	10.6
	Energy	AHB	6.9	5.2	7.5

[a] Average water shortage index (for agricultural and public sectors) over ten-day periods during non-typhoon seasons (%).
[b] Average annual food production (including rice, vegetables & fruits) (10^6 kg).
[c] Average annual hydropower benefits (10^6 in USD) of the Shihmen Hydropower Station and small-hydropower turbines.
[d] Occurrence frequency of a wet year (2005 is the representative in this study) was 20% during 2002 and 2016. A hydrological year starts from July to the next June.
[e] Occurrence frequency of a dry year (2011 is the representative in this study) was 80% during 2002 and 2016.
[f] Multi-year denotes the time series spanning from 2002 up to 2016 (14 years).
[g] Improvement rate (%), and M-5 rule curves simulation was the benchmark model.

sustainable development on the grounds that: (1) the innovative nature of this study lay in the application of small hydropower turbines for the first time in boosting the synergies of the WFE Nexus, and (2) AI optimization techniques were more beneficial to developing the potential installation of renewable energy in the existing water supply system, as compared with simulation techniques. Consequently, this study not only starts new anticipations on renewable energy production conducive to WFE Nexus synergies but also provides policymakers and stakeholders with practical solutions on small-hydropower applications in line with sustainable development, which could exert a far-reaching positive effect on the exploitation of new niches in the SHP and the fulfillment of future energy demands.

5. Conclusion

Fast development of urbanization and industrialization has triggered huge crises and challenges in the nexus management on water, food and energy demands. This study traced an overview on the prospect for small-hydropower generation in the light of sustainable development through exploring a holistic AI-based approach to recommending small-hydropower installation in close alliance with multi-sectoral water allocation for WFE Nexus management. The Shihmen Reservoir and its water supply system in northern Taiwan were the study case. The water allocation simulation based on M-5 rule curves served as a benchmark for comparative analysis. The combined optimal outcomes of multi-sectoral water allocation (acquired from the NSGA-II) and the optimal small-hydropower installation (acquired from the GA) demonstrated to mitigate the water shortage index, elevate the ratio of water storage to reservoir capacity, and enhance the hydropower output without a reduction in water supply. This delivered important messages that such combination not only could boost energy output but also promote water supply efficiency and food production from the perspectives of either year-round or multi-year reservoir operation. The results claimed that the proposed methodology could provide decision-makers and stakeholders with strategic policy recommendations on small-hydropower to sustain green growth in response to the inevitable trends of urbanization by effectively managing the WFE Nexus.

Today with rising energy prices and the growing demand for green energy worldwide, SHPs provide a great opportunity for clean energy conversion and management in Taiwan because air pollution becomes a serious concern in this island lately while nuclear power (more than 10% market share in energy profile) is scheduled to be completely phased out by 2025 upon the current governmental policy. Moreover, designs of small-hydropower turbines with advanced technical developments nowadays offer automated operation of SHPs and thus promote the installation and management of SHPs annexed to existing water supply systems. SHPs are therefore considered as a highly promising tool for expanding rural electrification as well as meeting sustainable development. It was also noted that the proposed optimization model could stimulate the synergies of the WFE Nexus in consequence of SHP installation but could not fully explore the potential installation of other renewable energy sources (e.g. solar PV power and wind power) associated with the optimal water allocation. That is to say, fusing the installation of solar PV power and wind power into the existing water supply system would contribute to further improvement on the renewable energy output. Additionally, this study concentrated on the long-term (ten-day period) operation models at the planning phase of SHP installation based on the capacity factor while the development of the short-term (daily or hourly) operation models at operating and managing phases in terms of efficiency–flow rate curve for reducing the uncertainty in the power output of the SHP would constitute future research. Follow-up studies will also extend to hybrid systems based on variable renewable sources with an impact assessment of complementarity on system reliability for promoting energy utilization efficiency [58].

As known, a huge demand for the rehabilitation of SHPs has already been raised globally, yet SHPs have not gained much attention in Taiwan to date. This is mainly due to high uncertainty in hydrological conditions and much lower purchase price in hydropower, as compared with the other green energy such as solar power and wind energy. To support the official mission – to be nuclear-free in Taiwan in 2025, this study aimed at exploring the potential of the SHP as a guideline for sustainable energy development. It is also expected that the benefit of the SHP would increase as the costs of SHP turbines would decrease owing to the growth in the installation base and the improvement in SHP techniques in the future. The proposed approach demonstrated that there could be a considerable scope and a great potential for recommending executable strategies on SHP development and management to optimize SHP profitability in the energy market in response to sustainable development. This study opens new prospects for green energy production because there is a huge yet untapped potential for (small) hydropower generation in most of the watersheds intertwined with densely distributed irrigation ponds (for instance, over 740 irrigation ponds are distributed over the Taoyuan area) in Taiwan, which could make significant contribution to fulfilling future energy needs.

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