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Greywater Reuse System Design and Economic Analysis for Residential Buildings in Taiwan

Yi-Kai Juan, Yi Chen * and Jing-Ming Lin

Department of Architecture, National Taiwan University of Science and Technology, Taipei City 10607, Taiwan; rik@mail.ntust.edu.tw (Y.-K.J.); leadtosky5@yahoo.com.tw (J.-M.L.)

* Correspondence: yichen0329@gmail.com; Tel.: +886-911-228-743

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Abstract: The concept of greywater recycling and reuse has gradually become one of the most important strategies in water stressed countries. Due to a high population density and uneven rainfall distribution, the annual average rainfall distribution per capita in Taiwan is one fifth of the global average, which makes Taiwan a seriously water-stressed country. This study used the unit of a family of four as the target and reexamined the zoning concepts of water usage areas, followed by integrating pipeline configuration, water storage design and a filtering system to propose an Interior Customized Greywater System (ICGS) which is based on the application for the family unit. This system can be customized and flexibly adjusted according to household space. In order to verify the feasibility and viability of system, this study performed system configuration and design based on real cases and proposed three scenarios to simulate a 20 year life cycle for cost economic analysis. The result reveals that this system has a minimum payback period of 4 years and provides investment incentives. For regions or countries which have higher water cost or are more water stressed, ICGS can significantly improve the processing and utilization of water.

Keywords: greywater reuse system; customized design; lifecycle cost analysis; residential buildings

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1. Introduction

Along with the gradual exhaustion of global water resources, a report from the United Nations has estimated that in the year 2025, 2.7 billion people will be facing water shortage problems which mean that the affected population will be 1/2–1/3 of the total population [1]. Water shortage problems have become one of the most urgent problems of the 21st century. Some researchers have suggested that water shortage will become more serious than oil shortage in the future [2]. Therefore, countries that are experiencing or partly experiencing drought have raised their awareness of water shortage hazards and many strategies aimed at reducing water usage and policies associated with water utilization [3], have been suggested.

Due to its high population density and uneven rainfall distribution, the annual average rainfall per capita in Taiwan is only one fifth of the global average [4]. Data from a United Nations report shows that Taiwan is the 18th most water stressed country in the world [1,5]. In Taiwan, the daily average water consumption per capita is 274 L which is higher than the 250 L suggested by the United Nations. In city regions such as Taipei, the daily average water consumption per capita reached 335 L. Among all types of water consumption, toilet flushing consumes the most water with 27% of the total, followed by showering and laundry. If an approximation is made based on Taiwan's population of 23 million, the annual water consumption on toilet flushing will be over 550 million metric tons [6].

Residential water consumption approximately makes up 10% of overall water consumption, preceded only by agricultural irrigation and industrial water consumption [7]. Previous studies have pointed out that in the face of a limited freshwater supply in the future, greywater recycling and reuse has been identified as one of the methods with extremely high potential and is also considered an important strategy in sustainable water management schemes [8]. Greywater recycling and reuse is done by filtering and recycling miscellaneous drain water from daily use and using it in secondary water applications [9,10]. Nevertheless, the low water cost in many countries, for example in Taiwan (based on total water cost for 200 m^3 of water per year, water cost in Taiwan is 1/5 of Japan, 1/4 of Singapore, 1/2 of Hong Kong [11], has caused a lack of incentive in the public for saving water and greywater recycling which results in worsening the water problem.

Previous studies on residential greywater reuse are mainly divided into two types of application configuration. The first type is a collective centralized greywater processing system design which is used by the entire building. But, due to problems such as bulkiness, complicated installation and high maintenance cost, follow up maintenance is relatively difficult [12–14]. The second type of greywater reuse design is targeted at single ownership household units [15,16]. Residential housing in Taiwan consists of mainly collective residential buildings and most of the households are independent from each other (buildings are not owned or used by a single household), therefore the aforementioned applications are not suitable in Taiwan.

In consideration for the localization of the solution and its suitability in Taiwan, this study proposed the Interior Customized Greywater System (ICGS) which is targeted at the unit of a family of four, and reexamines the zoning concepts of water usage areas to design an overall solution with pipeline configuration, water saving design and filtering mechanism. ICGS can be customized according to the space and structure of the household. In order to verify system's feasibility and viability, this study performed system installation and design based of real cases, simulated three future water consumption scenarios, and performed individual case economic analysis on the costs based on a 20 year life cycle to review the investment return of the system. The results from this study can be provided to countries which are similarly water stressed as reference.

2. Greywater System Review

Facing the challenge of the gradual exhaustion of water resources, many countries have actively developed greywater technologies and policies, as well as have applied them to agricultural and residential uses. For example, Los Angeles has reused 13%–65% of greywater saved from domestic households for agricultural irrigation [17]. A residential household in Brazil has used processed greywater for toilet flushing and has cut water consumption by approximately 29%–35% [18]. In Malaysia, 67% of water consumption is for the domestic usage, and greywater reuse for toilet flushing has the potential of 30% saving in water demand [19]. The operate rate of greywater facilities in South Korea is 26.5% through supply of two hundred million tons of greywater. In 2010, the Ministry of Environment announced a new law that enforced the installation of greywater reuse system for non-potable use, and people who need to build or remodel their buildings should install wastewater reclamation and reusing system which could reuse more than 10% of used water [20]. In Japan, the government does not provide incentives for household residents to implement greywater systems. However, 70% of Japanese support the utilization of rainwater or recycled water as they are highly aware of the need to conserve water, and water costs are relatively high in urban areas [20]. China's rapid economic growth has created a water crisis that the government has addressed through a number of policies including regulation requiring greywater treatment and water reuse for large scale institutional buildings and residential developments [20].

Some researchers have taken a step further and performed evaluation and analysis on the economic benefits of greywater systems. For example, Deepika Mandal et al. [21], from India, suggested the application of greywater processing and reuse systems in residential spaces. An up flow—down flow greywater treatment plant was installed in a basement and the greywater was reused for toilet flushing and vegetable irrigation. 48% of running water was saved and when kitchen waste water is excluded, the payback period is around 1.6 years. A study from Poland conducted a financial analysis on three types of showering facilities for different showering duration times. By using NPV calculations to analyze the water supply, drainage, and heating power consumptions when the family shower is used, the study found that if a drain water heat recovery system and a water flow limiter were installed for a shower system in a single building household, the discounted payback period (DPP) was less than a month. Furthermore, it was discovered that if the system was installed in high water consumption buildings such as multi-storey buildings or at swimming pools, more water can be recycled and reused while power consumption and the water cost will be reduced through the shower water recycling system [22].

On the other hand, Ghisi [23], compared the potential of the application of residential greywater system with the rainwater system. Results show that greywater systems have the highest cost efficiency. Mariana García-Montoya et al. [24], investigated greywater and rainwater recycling systems for domestic application in Mexico and performed cost and efficiency analysis on five different scenarios. Results revealed that the greywater system has a lower cost than running water and rainwater recycling systems and that the maximum economic efficiency is obtained by using both greywater and rainwater recycle systems.

3. Interior Customized Greywater System (ICGS) Design

3.1. Conventional Greywater System

Figure 1 depicts the concept of the conventional greywater reuse system for a multi-storey residential building in Taiwan. The system consists of three subsystems [25]:

- Collection of raw greywater: lateral pipes are installed to collect greywater from bath, shower, and washbasin to central vertical pipes.
- Conveyance and treatment of greywater: collected raw greywater is conveyed through these separate vertical pipes to the basement for treatment. Treated greywater is then pumped to the top of the building to the storage tank.
- Distribution of treated greywater: treated greywater is then gravitationally conveyed from the storage tank to each family unit in each flat.

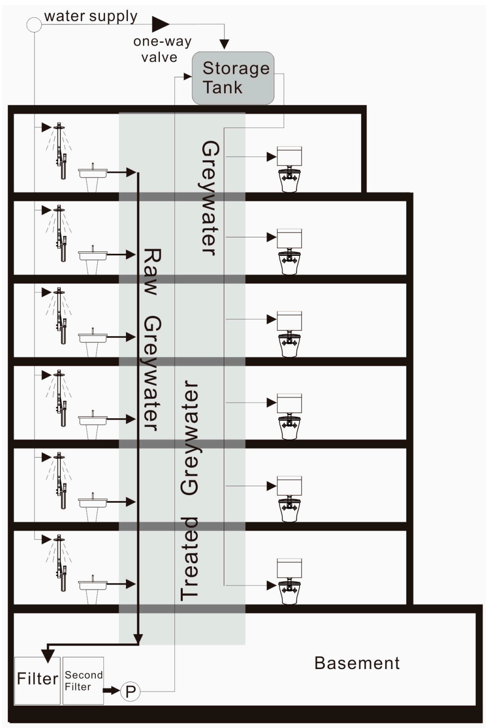


Figure 1. Conventional Greywater System.

Due to high maintenance costs of the filter devices and equipments of the system and difficulties in controlling water sources in each flat, the application of the conventional greywater reuse system in Taiwan is very limited. Since greywater has highly potential for water saving, developing technologies and solutions that can be more cost-efficient and customized for greywater reuse is crucial.

3.2. ICGS System

This study attempted to propose an Interior Customized Greywater System (ICGS) design with consideration for the water consumption and living habits in Taiwan. An analysis on the water usage areas, for example bathroom, kitchen, laundry, balcony (as shown in Figure 2), was performed. Afterwards, water quality was classified into two classes. First class water is freshwater supply, for example, water used in the shower, sink, and for laundry (blue line in Figure 2). Second class water is recycled and processed greywater that is used for toilet flushing and plant watering (green line in Figure 2). Between first class and second class water is "initial wastewater" which is collected after showering, laundry and hand washing (orange line is Figure 2). Water after toilet flushing is considered as "secondary wastewater" (purple line in Figure 2) and is out of the scope of this study.

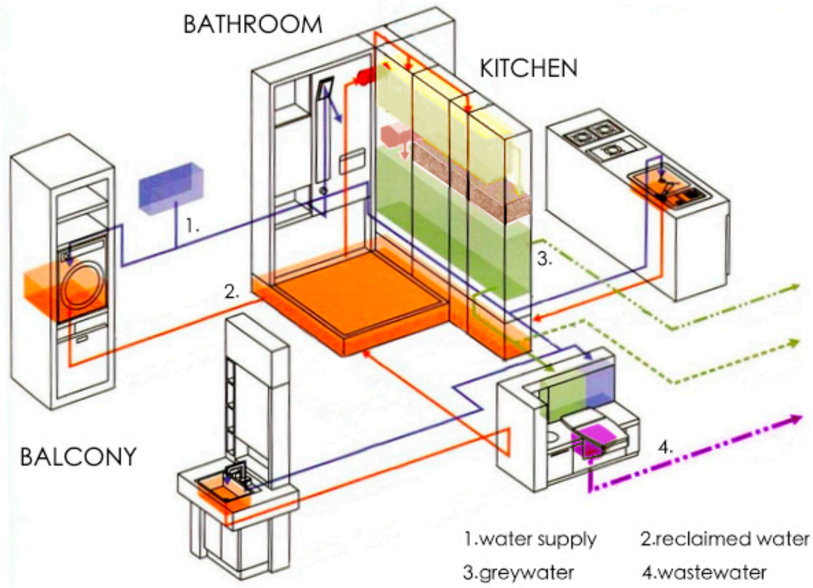


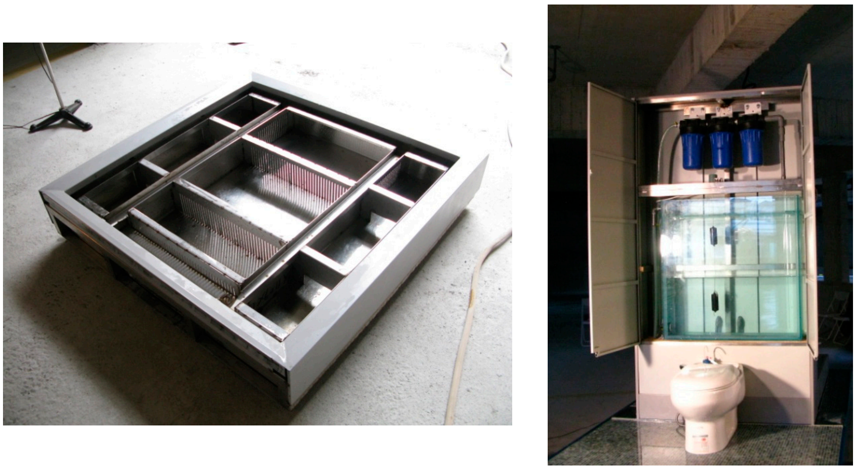
Figure 2. Conceptual diagram of Interior Customized Greywater System (ICGS).

Afterwards, a greywater processing system which integrates pipelines and greywater processing was constructed. This system included: a water storage system, filtering device, motor, and four subsystems of supply and drain pipes. The subsystems can be flexibly configured according to floor plan and spatial characteristics of the household. For example, water storage devices can be installed on the balcony if there is not enough interior space. If there is enough interior space, water storage devices can be installed near the wall around the bathroom so that the pipeline configuration cost can be reduced. The volume of the water storage tank is designed to satisfy water consumption by a family of five. The filtration device has individual access openings to allow replacement and regular maintenance.

From the perspective of supply and demand, according to water consumption information in Taiwan, each person consumes approximately 72 L of water on toilet flushing per day. On the other hand, water consumption for showering is approximately 50 L; general indoor water consumption is approximately 40 L and 50 L is used on laundry. ICGS can effectively integrate interior water supply and water usage areas while using processed greywater from showering, general indoor water use, laundry, etc., for toilet flushing or for watering plants on the balcony.

3.3. Greywater Processing Mechanism Design

ICGS can effectively integrate interior water supply and water usage areas, while reusing processed greywater from showers, regular interior water consumption and laundry etc. An effective filtering mechanism and filtering material is key to ensuring the quality of the recycled greywater [26]. In order to verify the operation of ICGS, this study made sectional prototypes to model the procedures in greywater processing: (1) Selection and precipitation: A water collection tank was installed (under the shower for example) inside the household, where filtration and sedimentation of hair and dander can be first performed (as shown in Figure 3a); (2) Filtration, includes three procedures: firstly, polypropylene filter is used to remove solid precipitates such as fine sand, mud, rust, microorganisms from the water, followed by using granular activated coal to absorb unpleasant color, odor, and to remove chemical substances. Lastly, mesh activated coal is used to absorb pleasant color, odor, chlorine gas, bleach, pesticides and organic chemical pollutants (as shown in Figure 3b); (3) Sterilization: performed by installing an ultra violet anti-bacterial device inside the water shortage installation according to operational requirement. After the various processing procedures, the filtered and sterilized greywater will be collected in the water storage installation, which is then provided for toilet flushing and exterior water usage (see Figure 3-bow). After verification, it was found that this system is able to effectively perform greywater processing procedures.



(**a**) (**b**)

Figure 3. Prototype model of greywater processing: (**a**) Primary filtration and sedimentation; (**b**) Filtration, sterilization and water storage.

4. System Application and Assessment

4.1. Case Study

In order to verify the feasibility and viability of system, this study performed system configuration and design based on a real case. The case study performed in a newly built collective housing located in Taipei city. The building consists of 12 floors, 40 households, and each household occupies an area of 24 *pings* (Taiwanese units of measurement; 1 *ping* = 3.306 m^2) and has 5 family members. In this case study, the balcony, kitchen and bathroom are adjacent, and the areas of water usage are centralized (as shown in Figure 4). According to the floor plan, the greywater processing design in ICGS was introduced and the design of the pipelines and subsystem configuration are given in Figure 5.

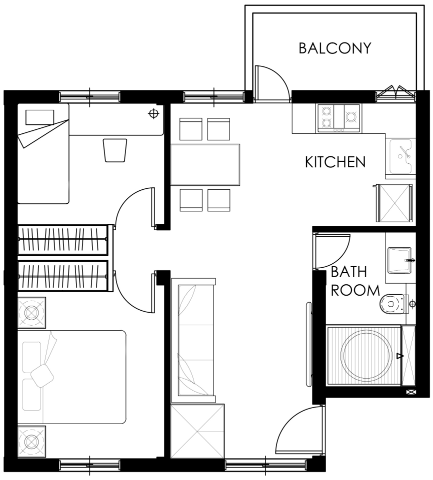


Figure 4. Case floor plan.

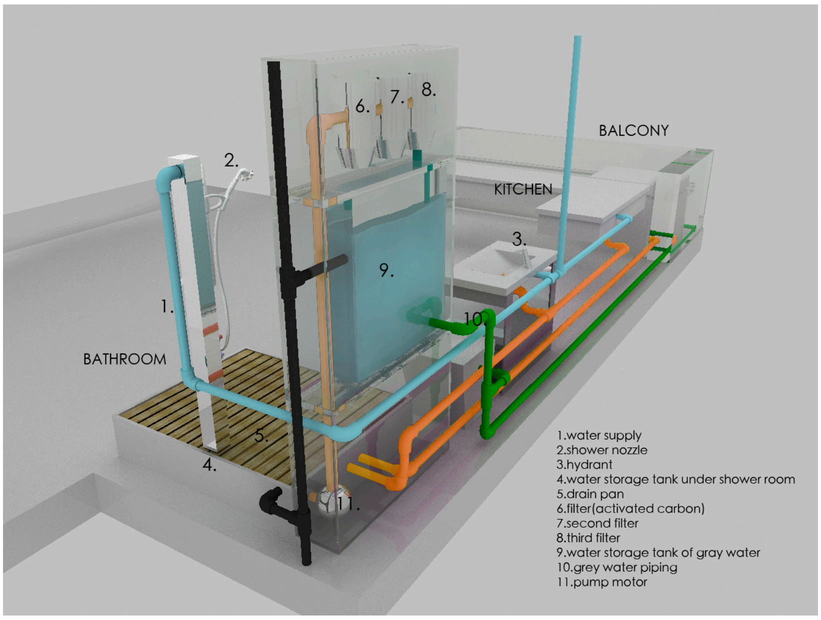


Figure 5. ICGS design introduced to the case.

4.2. Lifecycle Cost Analysis

The life cycle of ICGS includes the four items of (as shown in Table 1): (1) initial cost (A): including the costs of water storage installation, filtering device, motor, and drain pipe installation. Regardless of ICGS or the traditional method, sanitary facilities such as the shower and toilet are essential, therefore they are not included in the initial investment cost; (2) Annual maintenance cost (B): the cost of polypropylene filter is approximately 800 NT and requires replacement every 6 months; the cost of granular activated coal is approximately 960 NT and requires replacement every 6 months; the cost of mesh activated coal is approximately 1,080 NT and requires annual replacement. Annual maintenance and replacement cost is approximately 4,600 NT; (3) Operation cost: including water bill (C) and electricity bill (D). Taking a family of five as an example, the annual cost for a traditional water system, is approximately 7,800 NT. The usage of ICGS is estimated to save 55% in water consumption; therefore, 4,290 NT can be saved from the water bill. As for the electricity bill, ICGS involves the use of a motor which consumes 1,200 NT worth of electricity per year; (4) Replacement cost: the motor requires replacement approximately every 10 years and costs 3,500 NT. Residual value is not considered in this study.

Table 1. Life-cycle cost of conventional system and ICGS.

Attributes	Conventional System	ICGS	Year of Occurrence
Initial cost (A)	10,000	15,000	0
Maintenance cost (B)	500	4,600	annual
Operation cost: water bill (C)	7,800	3,510	annual
Operation cost: electricity bill (D)	400	1,200	annual
Replacement cost (E)	0	3,500	10

This small scale greywater system employed net present value (NPV) to reflect the life cycle costs (LCC) of the different categories; its lowest minimum acceptable rate of return (MARR) is 3%. This study analyzed the life cycle of the greywater system and the conventional system and proposed three investment assessment equations:

- $\mathrm{NPV} = \sum_{t=1}{}^{n} \frac{\mathrm{CFt}}{(1+i)^{t}} - \mathrm{cost}$
  CFt: Sectional cash flow; i: discount rate; Cost: initial investment cost.
- SIR = Total savings/total investment
- Total savings: The difference between the water bills of the two systems ($S_{conventional}$-S_{ICGS})Total investment: The difference between the total investment costs of the two systems ($I_{conventional}$-I_{ICGS}), including initial cost (A), Annual maintenance cost (B), Electricity bill (D), Replacement cost (E).
- Payback = Total investment expense/net annual income.

4.3. Scenario Simulation for Three Types of Economies

According to statistics, it costs 11.4 NT to produce 1 m^3 of water in Taiwan, and the average cost per unit is approximately 10.84 NT per metre cube (m^3) [27]. Comparing this with the cost in other countries, the cost in the United Kingdom is 77.83 NT, Germany 98.85 NT, the United States 24.33 NT, Hong Kong 17–36 NT and Japan 49–115 NT [11]. The water bill in Taiwan is relatively low which leads to a lack of public concern about water saving. This study interviewed officials and experts on water resource management and learned that a price hike in water rates is inevitable in the future. When the water cost in 2016 and 2015 is compared, the water cost in Taipei increased by 30% to cope with the water shortage problem. Furthermore, different water cost schemes will affect the analysis of life cycle costs. Therefore, this study has adopted three different scenarios for water cost cycle cost analysis was performed based on the different scenarios. Results are shown in Tables 2–4:

- Scenario 1: Future water cost remains unchanged.
- Scenario 2: Cost remains unchanged from the first to fifth year and surges by 30% from the sixth year until twentieth year.
- Scenario 3: Cost surges by 50% from the first to fifth year, 100% from the sixth to tenth year and 500% from the eleventh to twentieth year.

According to economic analysis of scenario 1, if the water bill remains unchanged in the future, ICGS can save 55% of interior residence water consumption which implies a reduction of 4,290 NT from annual water bill. From the life cycle cost analysis, ICGS does provide investment incentives (NPV = −14,075, SIR = 0.82, payback is unrecoverable). However, for a 50% increment in the water bill from the sixth to the twentieth year in scenario 2, ICGS is able to save 4,290 NT per year (first to fifth year) and 6,435 NT per year (sixth to twentieth year) from water bills during the two stages respectively. Table 3 shows that this scheme has investment potential (NPV = 18,568, SIR = 1.12, approximate payback of 12 years). Scenario 3 (as shown in Table 4), has three stages in its water billing. After calculation, an average of 6,435 NT can be saved each year (first to fifth year), 8,580 NT (sixth to tenth year) and 21,450 NT (eleventh to twentieth year), this shows that ICGS provides the maximum investment incentive (NPV = 173,838, SIR = 3.23, approximate payback of 4 years). When compared with scenario 2, the payback period significantly reduces as the water bill increases.

Since price hikes in the water bill is inevitable in Taiwan, this study performed 20 year life cycle cost analyses on scenarios 2 and 3. These scenarios have shown significant investment returns, and will have a lot of potential in application and promotion to the market in the future.

Table 2. Economic analysis of scenario 1.

Cost Items		Base Date Cost (NT$)	Year of Occurrence	Present Value (NT$)	Difference
Initial invest cost	Greywater Traditional	15,000 10,000	Base Date Base Date	15,000 10,000	5,000
Maintenance and Repair cost	Greywater Traditional	4,600 500	annual annual	68,436 7,439	60,998
Residual value	Greywater Traditional	0 0	20 20	0 0	0
Operation cost	Greywater Traditional	1,200 400	annual annual	17,853 5,951	11,902
Water bill	Greywater Traditional	3,510 7,800	annual annual	52,220 116,044	63,824
Pump cost	Greywater Traditional	3,500 3,500	10 10	2,604 2,604	0
Present value of greywater system			Total	156,114	
Present value of traditional system			Total	142,038	
NPV result			NPV < 0	−14,075	
SIR result			SIR < 1	0.82	
Payback result			Payback period	unrecoverable	

Table 3. Economic analysis of scenario 2.

Cost Items		Base Date Cost (NT$)	Year of Occurrence	Present Value (NT$)	Difference
Initial invest cost	Greywater Traditional	15,000 10,000	Base Date Base Date	15,000 10,000	5,000
Maintenance and Repair cost	Greywater Traditional	4,600 500	annual annual	68,436 7,439	60,998
Residual value	Greywater Traditional	0 0	20 20	0 0	0
Operation cost	Greywater Traditional	1,200 400	annual annual	17,853 5,951	11,902
Water bill	Greywater	3,510 5,265	annual (1st–5th year) annual (6th–20th year)	16,075 62,853	96,468
	Traditional	7,800 11,700	annual (1st–5th year) annual (6th–20th year)	35,722 139,674	
Pump cost	Greywater Traditional	3,500 3,500	10 10	2,604 2,604	0
Present value of greywater system			Total	182,822	
Present value of traditional system			Total	201,390	
NPV result			NPV > 0	18,568	
SIR result			SIR > 1	1.12	
Payback result			Payback period	Approximately 20 years	

Table 3 shows that NPV value >0 and SIR value >1, indicating that this scheme has investment potential. Payback period is approximately 12 years based on time value calculation.

Table 4. Economic analysis of scenario 3.

Cost Items		Base Date Cost (NT$)	Year of Occurrence	Present Value (NT$)	Difference
Initial invest cost	Greywater	15,000	Base Date	15,000	5,000
	Traditional	10,000	Base Date	10,000	
Maintenance and Repair cost	Greywater	4,600	annual	68,436	60,998
	Traditional	500	annual	7,439	
Residual value	Greywater	0	20	0	0
	Traditional	0	20	0	
Operation cost	Greywater	1,200	annual	17,853	11,902
	Traditional	400	annual	5,951	
Water bill	Greywater	5,265	annual (1st–5th year)	24,112	251,737
		7,020	annual (6th–10th year)	32,150	
		17,550	annual (11th–20th year)	149,705	
	Traditional	11,700	annual (1st–5th year)	53,583	
		15,600	annual (6th–10th year)	71,443	
		39,000	annual (11th–20th year)	332,678	
Pump cost	Greywater	3,500	10	2,604	0
	Traditional	3,500	10	2,604	
Present value of greywater system			Total	309,860	
Present value of traditional system			Total	483,698	
NPV result			NPV > 0	173,838	
SIR result			SIR > 1	3.23	
Payback result			Payback period	Approximately 4 years	

Table 4 shows that NPV value >0 and SIR value >1, indicating that this scheme has investment potential. Payback period is approximately 4 years based on time value calculation.

5. Conclusions

Facing the global challenge of water scarcity situations, many countries and organizations have raised their awareness of water shortage hazards and proposed effective policies to reduce water usage. Greywater has a high potential for recycle and reuse to provide sufficient quantity of water for human beings, however, its applications are still limited. There is a need to continuously develop the technologies, actions, and strategies for greywater reuse at household level to increase the reuse practices at grass root level. The greywater processing system suggested by Mandala [20], in India and the case "GW1" suggested by Nodle & Patner [12], in Berlin, Germany are based on installing greywater processing systems in basements, which is unsuitable for the densely populated metropolitan households in Taiwan. Differing from greywater reuse studies conducted in other countries and regions, this study attempted to design a greywater reuse system based on the architectural style and water consumption behavior in Taiwan. This system included an integrated design of water storage device, filtering device, motor and drain pipes where flexible configuration can be made according to residential floorplans and spatial characteristics. Through critical analysis of using the 20 year life cycle simulation in three proposed scenarios, where the water bill is incremented gradually, it was found that in scenarios 2 and 3 the system provided investment incentives, with payback periods of 12 years and 4 years and the SIRs are 1.12 and 3.23 respectively. Compared with previous international studies, the ICGS has demonstrated its potentials and advantages on economic incentives. Especially for regions and countries where water is expensive or if they are relatively water-stressed, the implementation of ICGS into domestic households will largely contribute to more water saving.

Nevertheless, this system has some implementation limitations. Firstly, if water usage areas (such as bathroom, kitchen etc.) are dispersed throughout the household, the cost of pipeline configuration will be significantly increased, and the payback benefits will be reduced thus possibly affecting investment and implementation assessment. Secondly, if the residential area is too small, the implementation of ICGS requires installation of extra water storage and filtering devices thus increasing the implementation difficulty of the entire system. Thirdly, If ICGS is applied in other regions or countries, considerations for the region's architecture, consumption habits, and climate conditions are required and this may affect system operation and investment return. Further study can focus on constructing a complete set of design principles and suggestions based on the architecture of different regions and used as references for future implementation assessment.

Author Contributions: Yi-Kai Juan led the research activities and designed the system framework; Yi Chen and Jing-Ming Lin performed the experiments and data analysis.

Conflicts of Interest: The authors declare no conflict of interest.

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