Feasibility Analysis of Rainwater Harvesting Systems for Non-potable Water in a Public Building

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水資源には限りがあり、雨水を貯めて非飲料水として活用することは大切だ。ではどのようなシステムが有効なのか。その答えを北九州大学における実証試験を通じて検証した。

Abstract

Rainwater harvesting is one of the important measures to alleviate water scarcity. However, the performance of rainwater harvesting systems (RWH) in different regions and buildings is different. Public buildings have more non-potable water demands, such as air conditioning cooling and building cleaning. Some demands are stable throughout the year, but others are seasonally changed, especially for cooling. The changing demands may or may not increase the feasibility of RWHs. In order to explore the feasibility of RWHs in public buildings, a Japanese campus was selected as a case study. A water balance model and a life cycle cost model with actual monitoring data were carried out to simulate the water-saving performance and the economic benefits of the RWH under different non-potable water demand scenarios. The results show that the installation of RWH in public buildings has prominent water-saving performance and economic benefits. The optimal rainwater tank size of RWH should be expanded when the non-potable water demand changes seasonally. The results obtained can not only serve as a comparison tool for other studies, but also provide data support for large-scale RWH research to promote the RWH.

Keywords Rainwater harvesting system, public building, water conservation, economic analysis

1. Introduction

With the trend of increasing water demand caused by global warming and population growth, water scarcity worldwide is getting worse and worse. According to the prediction of the World Water Assessment Program (UNESCO WWAP), there will be 47% of the world population living in water scarcity regions in 2030[1]. Thus, alternative water sources such as rainwater have been widely used in many developed and developing countries to alleviate the pressure on water supply from centralized main water plants. Rainwater harvesting systems (RWHs) are derived for supplying rainwater to buildings as decentralized water reuse systems to substitute non-potable water because some water uses do not rely on high-quality water such as laundry, toilets, and irrigation taps[2].

Rainwater is one of the most common alternative water sources. Rainwater harvested by RWH can be easily reused without complicated purification facilities after the first washing, and can even be reused directly in some countries[3]. However, the water-saving efficiency of RWH is limited by many factors, such as the amount of precipitation and the rainwater capture areas of buildings[4]. This has led to the fact that the water-saving efficiency of RWH in single-family houses is higher than that in multi-store houses under the same capture areas, and the water-saving efficiency of RWHs is negative in cold semi-arid and warm desert areas[5]. As a result, the economic benefits brought by the RWHs in some building types and some regions cannot offset the investment cost. Therefore, although most countries encourage the installation of RWHs on new buildings, there are still several regions that still lack confidence in the economic benefits of spreading RWH to cities[6].

Compared with residential and commercial buildings, public buildings have a larger scale of non-potable water consumption and more non-potable water uses, such as cleaning and sanitation[7]. Previous studies have shown that installing water reuse systems in campus buildings is more feasible than other building types. However, the evaluation of installing RWH in this type of building is still in its infancy[8]. Evaluating the water-saving performance and economic benefits of RWH in campus buildings, which is a largely under-explored domain in public buildings, has far-reaching significance for the promotion of RWH.

Therefore, the motivation of this work is to encourage the use of RWHs in the context of public buildings, as an integral part of sustainable water management. This study aims to evaluate the feasibility of installing a large-scale RWH on campus in Japan. A water balance model and a life cycle cost model are used to determine the water-saving efficiency and economic benefits of the RWH. The results found in this research can serve as a comparison tool for other studies and provide data support for stakeholders to popularize HRG.

2. Material and methods

2.1 Study area and system description

In order to explore the feasibility of RWHs in public buildings, a campus located in Kitakyushu, Fukuoka, Japan was selected as a case study. The layout of the campus is shown in Fig.1. The campus includes 7 buildings with 53214.35 m^2 of service areas and 10632 m^2 of rainwater capture areas. An integrated RWH is stalled in one of the buildings, which is mark with a red dot in Fig.1. All rainwater from the campus is transferred to the RWH and distributed to water end-uses.

The RWH on the campus includes rainwater storage tanks, a piece of filtration equipment, rear rainwater tanks to store the treated rainwater, and the corresponding pumps and plumbing systems (Fig.2). Thus, there is no first flushing device in the RWH. Main water supplements are directly supplied into the rear rainwater tanks to avoid insufficient rainwater supply because of the scarcity of rainwater.

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Fig. 1 Location of the study area

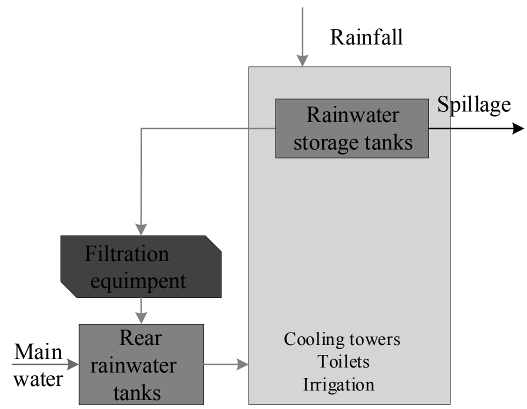

Fig. 2 Lay out of the RWH

Non-potable water end-uses of the campus include cooling towers for air conditioning and electricity systems, irrigation, and toilets of all the buildings. The water consumption data of the campus is obtained by field investigation of the water consumption inventory in the campus. Fig.3 shows the annual trend of those water consumption. According to Fig.3, there are two kinds of water consumption modes on the campus, one is the water consumption of toilets and irrigation, the other is the water consumption of cooling towers. The former water consumption has a small change in a year. The later water consumption mode, however, has obvious seasonal characteristics, which is topped in summer and lower in other seasons. Thus, in this paper, three

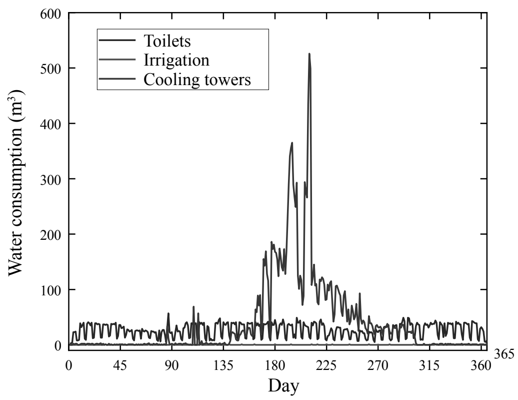

Fig. 3 Non-potable water consumption of the campus

kinds of non-potable water demands are assumed to evaluate the feasibility of the RWH in the public building: only for cooling towers, only for toilets and irrigation, and for all the non-potable water end-uses. The annual water demands of those scenarios are listed in Table 1.

Table 1 Annual water demand of the public building

	Scenario 1: Cooling towers	Scenario 2: Toilets and irrigation	Scenario 3: Cooling towers, toilets, and irrigation
Annual water demand	14879 m^3	9847 m^3	24726 m^3

2.2 Methodology

2.2.1 Water balance model

Water balance model is used widely in the simulation of RWHs because it can accurately describe the operation state of RWHs according to daily step size. The mathematical expression is:

$$I_t + R_{t-1} + SUP_t = R_t + SPI_t + Y_t \tag{1}$$

Where I_t is the rainwater harvested by rainwater storage tanks (m^3); R_{t-1} is the rainwater remaining in rainwater tanks at the beginning of time step t (m^3); SUP_t is the main water supplements from municipal pipelines (m^3); R_t is the rainwater remaining in rainwater tanks at the end of time step t (m^3); SPI_t is the rainwater spillage of rainwater tanks (m^3); and Y_t is the rainwater yield of RWHs.

"Yield after spillage" algorithm (YAS) assumes that the yield of rainwater in rainwater tanks occurs after excess rainwater spillage. This algorithm can simulate the operation state of RWHs conservatively to obtain more appropriate results than the "yield before spillage" algorithm (YBS)[9]. Thus, in this paper, YAS is used to carry out the simulation of the RWH:

$$I_t = \frac{\varphi F H_t}{1000} \tag{2}$$

$$Y_t = \begin{cases} R_{t-1} + I_t & if\ R_{t-1} + I_t - D_t < 0; \\ D_t & if\ R_{t-1} + I_t - D_t \geq 0; \end{cases} \tag{3}$$

$$R_t = \begin{cases} R_{t-1} + I_t - Y_t & if\ R_t + I_t - V < 0; \\ V - Y_t & if\ R_t + I_t - V \geq 0; \end{cases} \tag{4}$$

$$SUP_t = \begin{cases} D_t - R_{t-1} - I_t & if\ R_{t-1} + I_t - D_t < 0; \\ 0 & if\ R_{t-1} + I_t - D_t \geq 0; \end{cases} \tag{5}$$

$$SPI_t = \begin{cases} 0 & if\ R_{t-1} + I_t - D_t < 0; \\ R_t + I_t - V & if\ R_{t-1} + I_t - D_t \geq 0; \end{cases} \tag{6}$$

Where φ is the runoff coefficient (dimensionless, 0-1), and 0.8 is considered in this paper; F is the rainwater capture areas (m^2); H is the precipitation (mm); D is the non-potable water demand of rainwater (m^3); and V is the size of rainwater tanks (m^3).

Water-saving efficiency (W, %) is the proportion of non-potable water that can be replaced by reusing rainwater:

$$W = 100 \times \frac{\sum Y_t}{\sum D_t} \tag{7}$$

Non-potable water supply capacity (NSC, %) refers to the proportion of days in a year that the main water is not necessary to be supplied to the RWH:

$$NSC = 100 \times \frac{D_{tot} - D_{sup}}{D_{tot}} \tag{8}$$

Where D_{tot} is the total number of days in a year of 365 d; D_{sup} is the number of days that the main water supplements to the RWH when the non-potable water yield from the RWH cannot meet the demand (d).

Rainwater spillage rate (R, %) is the proportion of the excess rainwater spilling to the harvested rainwater:

$$R = 100 \times \frac{\sum I_t}{\sum SPI_t} \tag{9}$$

In the simulation process, the selection principle of rainfall time series should be long enough to reflect the stability of rainfall and the time resolution of rainfall is preferable into hour interval than daily interval than month interval. However, previous studies have shown that 20-year daily rainfall data can achieve similar results to 50-year hourly rainfall data in continuous simulation[10]. Thus, a 20-year daily rainfall data from Japan Meteorological Agency is used in this paper[11].

2.2.2 Economic analysis

Life cycle cost model is used to determine the economic benefits of the RWH in the campus. A life cycle cost model includes the investment cost, operation and maintenance cost, and dismantling cost of the RWH. A 20-year life cycle is assumed of the RWH because the life cycle of almost all pumps and valves is 20 years, and there is no replacement process in the 20-year life cycle. On the other hand, because the dismantling cost has less proportion during the whole life cycle cost[12], the dismantling cost is ignored in this paper. The rainwater tank is the most expensive component of RWHs in the investment cost compared to plumbing systems, thus the investment cost of the RWH includes rainwater tank cost, pumps cost, and filtration equipment cost. The ideal life cycle cost model is:

$$COST_{RWH} = COST_V + COST_C \tag{10}$$

Where $COST_{RWH}$ is the life cycle cost of RWH (JPY); $COST_V$ is the cost of rainwater tank (JPY); $COST_C$ is the other components cost (JPY). The cost of RWH's components is listed in Table 2.

Table 2 The cost of RWH's components

Items	Price (JPY)
Rainwater tanks	9730 per m^3
Filtration equipment	700,000
Pumps	900,000

The direct economic benefits of RWH is to reduce water tariffs:

$$BENEFIT_{RWH} = \sum \frac{Y_t \times COST_W}{(1+r)^y} \tag{11}$$

Where $BENEFIT_{RWH}$ is the economic benefit of RWH (JPY); $COST_W$ is the water tariff of the Kitakyushu (JPY); r is the discount rate of Japan (%), which is 3.5% according to the Global Economic Data[13]; y is the year in the life cycle of the RWH. The water tariff of Kitakyushu includes basic fee and usage fee, and the specific price is shown in Table 3.
Benefit-Cost rate (BCR) was used to evaluate the investment feasibility of RWHs:

$$BCR = \frac{BENEFIT_{RWH}}{COST_{RWH}} \tag{12}$$

If the BCR is more than 1 shows that the RWH has economic benefits and it's feasible for investment, otherwise it is negatively feasible to install the RWH in the campus building. In addition, the sale tax rate is 8% in this paper.

Table 3 The water tariffs of the Kitakyushu, Japan (monthly)

	Price (JPY)
Base	4500
1 m^3 – 25 m^3	122
26 m^3 – 50 m^3	156
51 m^3 – 200 m^3	208
201 m^3 – 1000 m^3	288
1001 m^3	310

Net present value (NPV) is used to determine the cash flow of the RWH on the campus over a 20-year life cycle:

$$NPV = BENEFIT_{RWH} - COST_{RWH} \tag{13}$$

3. Results and discussion

3.1 water-saving efficiency

Water-saving efficiency of RWH on the campus under three non-potable water demand scenarios is shown in Fig.4.

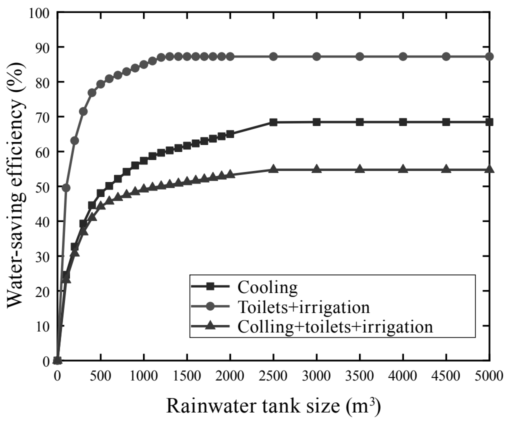

Fig. 4 Water-saving efficiency of RWH on the campus

According to Fig.4, the water-saving efficiency of installing RWH on campus can be divided into three stages: rapid rise stage, slow rise stage, and threshold stage. The rainwater tank size before the water-saving efficiency of RWH reaches the threshold is assumed to be the optimal rainwater tank of RWH. First, when the non-potable water demand scenario only has toilets and irrigation, the water-saving efficiency threshold of RWH is 87.23%; when the non-potable water demand is only for cooling towers, the water-saving efficiency threshold of RWH drops to 68.46%. Finally, when all non-potable water demands are provided by rainwater, the water-saving efficiency drops to 54.76%. This indicates that no matter how to increase the rainwater tank size, RWH will not be able to meet the demand for non-potable water on campus. In addition, since all the roofs of the case campus are set as rainwater capture areas, it is impossible to increase the non-potable water-saving efficiency by increasing the rainwater capture areas. This indicates that installing a large-scale RWH on campus will not be able to meet all the non-potable water demands.

3.2 non-potable water supply capacity

The non-potable water supply capacity of RWH on the campus is shown in Fig.5. Interestingly, although the trends of the curves under the three non-potable water demand scenarios are similar to those in Fig.4, the order of the curve thresholds under the three scenarios is different from Fig.4. The highest value of NSC occurs when rainwater is only used for cooling tower supplemental water (the water demand varies greatly with the seasons), reaching 92.88%. The second is to use rainwater only for toilets and irrigation, which is 83.38%. When all non-potable water demands are provided by rainwater, the NSC is only 66.30%.

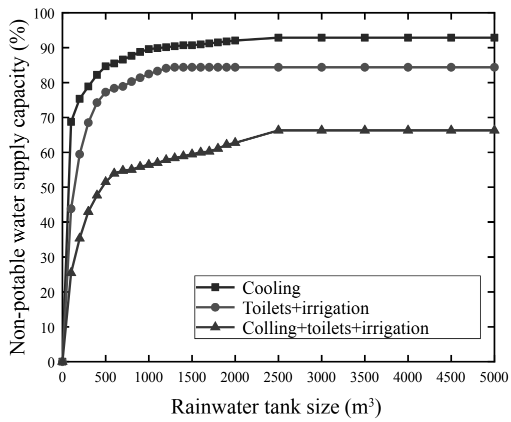

Fig. 5 non-potable water supply capacity of RWH on the campus

The water-saving efficiency of scenario 1 is lower than that of scenario 2, but the number of stable water supply days (NSC) of scenario 1 is higher than that of scenario 2 is that the rainy season in the study area is concentrated in the peak water demand period of scenario 1, thus more rainwater is used instead of spilling out of the rainwater tank (Fig.6). Compared to Scenario 1 with Scenario 3, in which the demand for non-potable water varies with the seasons, Scenario 3 has a much lower NSC value than Scenario 1 due to the greater water demand. RWH under scenario 3 cannot meet non-potable water demand nearly half of the year.

According to Fig.6, in Scenario 1 and Scenario 3, almost no rainwater spills from the rainwater tank when the water-saving efficiency of RWH reaches the threshold (2500 m^3, rainwater spillage rate is 7.3% and 0%, respectively). In addition, it can be seen that in the non-potable water demand mode of scenario 2, when the rainwater tank of the RWH is less than 600 m^3, the rainwater spillage rate is smaller than that of scenario 1.

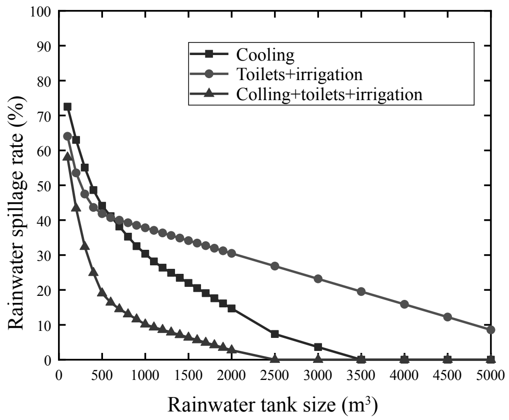

Fig. 6 Rainwater spillage rate of RWH on the campus

This is still caused by the short peak period of non-potable water in the rainwater demand model of scenario 1, and the smaller water tank cannot store a large amount of rainwater for use during the peak non-potable water demand. A seasonal demand pattern places a higher demand on the storage capacity of RWH.

3.3 Economic benefits

The economic benefits of RWH on campus are shown in Fig.7. It can be seen from Fig.7 that regardless of whether the non-potable water demand changes with the seasons, it is economically feasible to install RWH in public buildings. In scenario 1 and scenario 2, when the rainwater tank of RWH exceeds 4000 m^3 and 3500 m^3, the BCR is less than 1. However, the water-saving efficiency thresholds of Scenario 1 and Scenario 2 are reached when the rainwater tank size is 2500 m^3 and 1300 m^3, respectively. This indicates that when rainwater is only used for air conditioning cooling towers and only for toilets and irrigation, there is no need to expand the rainwater tank size of RWH to a higher level.

From the value of BCR, when the water-saving efficiency reaches the threshold, the BCR of RWH is 1.62 (rainwater is used only for cooling towers), 2.52 (rainwater is used only for toilets and irrigation), and 2.2 (rainwater is used for cooling towers, toilets, and irrigation), respectively. This shows that when rainwater is only used for toilets and irrigation, RWH has stronger investment potential. However, BCR is different from the NPV, the BCR emphasizes the investment feasibility that it does not present the overall monetary value of the benefits and costs[14], while the NPV emphasizes the absolute of monetary value.

The NPV of RWH on campus for 20 years is shown in Fig.8. It can be seen from Fig.8 that when rainwater is used for all non-potable water supplies, although the water-saving efficiency is low, the NPV value is the highest due to the high water-saving amount. This shows that in this scenario, although the reliability of water supply cannot be guaranteed, the economic benefits or RWH are the highest. Interestingly, the highest value of NPV of RWH in the three scenarios occurs when the rainwater tank volume is 900 m^3 (25,044,591 JPY), 500 m^3 (26,876,332 JPY) and 700 m^3 (41,900,728 JPY), respectively, instead of the threshold of water-saving efficiency, which 2500 m^3 (16,667,382 JPY), 1300 m^3(22,033,471 JPY), and 2500 m^3 (32,612,799 JPY). This value appears in the first stage of the RWH water-saving efficiency curve, that is, the rapid rise stage.

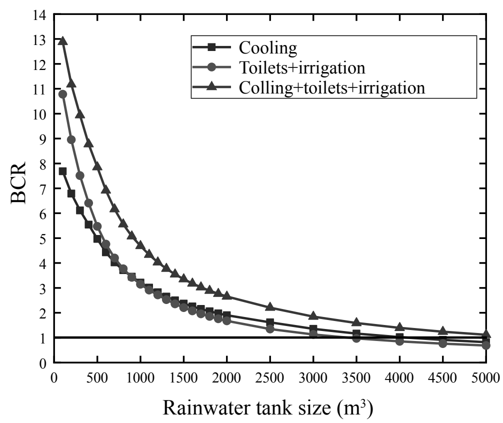

Fig. 7 BCR of RWH on the campus

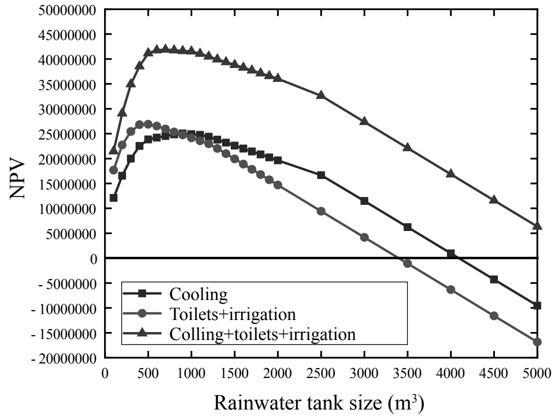

Fig. 8 NPV of RWH on the campus

4. Conclusion

In order to evaluate the feasibility of rainwater harvesting systems in public buildings, an on-site decentralized rainwater harvesting system on a Japanese campus is selected in this study. The water-saving performance and economic benefits of RWH are analyzed. The conclusions are as follows:

Installing RWH in public buildings has a prominent water-saving efficiency, but it cannot meet all non-potable water demands. When all non-potable water is replaced by rainwater, RWH needs to rely on main water for almost half of the year. A seasonally changing demand for non-potable water places higher requirements on the rainwater tank size of RWH. Regardless of the water demand model, it is economically feasible to install RWH on campus. However, the maximum economic benefits of RWH do not appear at the threshold of water-saving efficiency, but at the later stage of the rapid rise stage of water-saving efficiency. As the water-saving efficiency of RWH enters a period of slow increase, the economic benefit of RWH has a downward trend. Therefore, a reasonable selection of RWH rainwater tank size between the best water-saving efficiency and the best economic benefits has become the focus of RWH design in public buildings.

Future research should increase the case studies of RWH's feasibility analysis in different building types, especially with actual data as the background to improve the accuracy of the results. In addition, in response to the economics of RWH, especially the investment in the operation phase of RWH, more accurate modeling should be carried out to more accurately analyze the economic benefits of RWH in different life cycles.

References

1. World Water Assessment Programme (UNESCO WWAP). [cited 2020 23 October].: http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr/wwdr4-2012/.
2. Devkota, J., H. Schlachter, and D. Apul, Life cycle based evaluation of harvested rainwater use in toilets and for irrigation. Journal of Cleaner Production, 2015. 95: p. 311-321.
3. Jing, X., et al., Assessing efficiency and economic viability of rainwater harvesting systems for meeting non-potable water demands in four climatic zones of China. Resources, Conservation and Recycling, 2017. 126: p. 74-85.
4. Leong, J.Y.C., et al., Quantification of mains water savings from decentralised rainwater, greywater, and hybrid rainwater-greywater systems in tropical climatic conditions. Journal of Cleaner Production, 2018. 176: p. 946-958.
5. Ali, S., S. Zhang, and T. Yue, Environmental and economic assessment of rainwater harvesting systems under five climatic conditions of Pakistan. Journal of Cleaner Production, 2020. 259.
6. Bashar, M.Z.I., M.R. Karim, and M.A. Imteaz, Reliability and economic analysis of urban rainwater harvesting: A comparative study within six major cities of Bangladesh. Resources, Conservation and Recycling, 2018. 133: p. 146-154.
7. Ward, S., F.A. Memon, and D. Butler, Performance of a large building rainwater harvesting system. Water Res, 2012. 46(16): p. 5127-34.
8. Alim, M.A., et al., Feasibility analysis of a small-scale rainwater harvesting system for drinking water production at Werrington, New South Wales, Australia. Journal of Cleaner Production, 2020. 270.
9. Jing, X., et al., Analysis and Modelling of Stormwater Volume Control Performance of Rainwater Harvesting Systems in Four Climatic Zones of China. Water Resources Management, 2018. 32(8): p. 2649-2664.
10. Zhang, S., et al., Performance assessment of rainwater harvesting systems: Influence of operating algorithm, length and temporal scale of rainfall time series. Journal of Cleaner Production, 2020. 253.
11. Japan Meteorological Agency. [cited 2020 27 September]. http://www.jma.go.jp/jma/index.html.
12. Leong, J.Y.C., et al., Life-cycle assessment and life-cycle cost analysis of decentralised rainwater harvesting, greywater recycling and hybrid rainwater-greywater systems. Journal of Cleaner Production, 2019. 229: p. 1211-1224.
13. Global Economic Data, Indicators, Charts & Forecasts. [cited 2020 29 September]; Available from: https://www.ceicdata.com/en.
14. Cbabuilder, 2016. Comparing NPV and BCR viewed 1/5/16. http://www.cbabuilder.co.uk/Results3.html.