Managing Water and Energy on Small Touristic Islands

Study case Caye Chapel

Francisco Javier Contreras Navarro

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On the cover

The cover image shows the island Caye Chapel. The image was retrieved from https://www.cayechapel.com (accessed December 01, 2021).

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By

Francisco Javier Contreras Navarro

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	Prof.dr. Jan Peter van der Hoek,	TU Delft
	Dr. Stefan Pfenninger,	TU Delft

TU Delft

Managing Water and Energy on Small Touristic Islands: Study case Caye Chapel

Francisco Javier Contreras Navarro *

**Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands (e-mail: F.J.ContrerasNavarro@student.tudelft.nl).*

Abstract: Small islands that support urban communities provide a unique opportunity to study the urban water cycle, its energy needs, and possible links to renewable energy. The aim of this paper is to explore to what extent an island's urban water cycle and the renewable electricity production system required to satisfy the urban water cycle's demand can become sustainable using Caye Chapel (Belize) as a study case. For this research, the water-energy system is the urban water cycle and the renewable electricity production for the urban water cycle. Twelve alternatives were proposed for the water-energy system. The different alternatives are divided among those that consider the reuse of wastewater, rainwater harvesting, and the use of wind turbines, PV panels, or both for the renewable electricity production. Then, those alternatives were optimized to produce the minimum water demand shortage, minimum amount of treated water that is not reused, and renewable electricity shortage. Later, the optimized alternatives are evaluated using multi-criteria decision analysis (MCDA). It was observed that the alternatives that only consider one renewable source for the electricity generation and do not consider the reuse of wastewater, are outperformed by the alternatives that consider more than one renewable source and reuse the treated wastewater.

Keywords: Urban water cycle; Renewable energy; Water management; Multi-objective optimization; Multi-criteria decision analysis.

1. INTRODUCTION

Water and energy are two sectors inextricably linked, and both of them are lifeline sectors for the well-being and economic development of societies (Hamiche et al., 2016; Olsson, 2013; Segurado et al., 2018). The United Nations (UN) recognizes the relevance of these two sectors by including them in the 17 Sustainable Development Goals (SDGs) from the 2030 Agenda for Sustainable Development, presented in 2015. The SDG 6 (Clean water and sanitation) aims to ensure the availability and sustainable management of water and sanitation and the SDG 7 (Affordable and clean energy) aims to ensure access to affordable, reliable, sustainable, and modern energy for all. Unfortunately, according to Olsson (2013), the security of water and energy is being threatened by climate change. Water security depends on the availability of energy to provide the water. However, the energy availability can be affected, for example, during a heat wave. Under these circumstances, there would be a high risk of energy industries reducing or shutting down their production due to a lack of cooling water (Olsson, 2013). Moreover, according to the United Nations and Division for Sustainable Development (2010), small islands are territories prone to be more affected due to their small size, remoteness, high susceptibility to natural hazards, and low economic resilience. In addition, their fragile environments make more difficult the pursuit of sustainable development (Segurado et al., 2018).

Existing literature studies the implementation of renewable energy systems like wind turbines (Bağcı, 2009; Ntziachristos et al., 2005; Papathanassiou and Boulaxis, 2006; Parissis et al., 2011; Ulleberg et al., 2010) or PV panels (Bağcı, 2009; Kougias et al., 2016) to satisfy, partially or fully, the electricity demands of islands. They aim to reach a stand-alone system by increasing the renewable energy penetration in the energy grid and reducing the use of fossil fuels. Other papers study the interaction between renewable energy and water systems on small islands. They focus mainly on how to produce freshwater from desalination facilities that are powered by renewable energy sources (Cabrera et al., 2021; Calise et al., 2020; Melián-Martel et al., 2021; Segurado et al., 2015; Spyrou and Anagnostopoulos, 2010; Triantafyllou et al., 2021). It has been found that the nexus between renewable energy and the water cycle contributes to the better integration of intermittent Renewable Energy Sources (RES) and decarbonizing the water cycle (Melián-Martel et al., 2021).

According to the Clean energy for EU islands secretariat (Euopean Comission, 2022), the best practices to supply electricity on touristic islands are using subsea cables connected to the mainland, fossil fuels, or both, and on a smaller scale, the use of renewable energies. For example, Cres-Lošinj (Croatia), has a population of 10,895 residents and hosts up to 30,000 visitors in summer. The electricity is supplied through a subsea cable connected to the mainland, and there are some houses, schools, and companies that use photovoltaic (PV) panels. Saint Martin (France) is a touristic island with a fixed population of 36,000 that increases due to tourism between November and April. The energy system is powered by a fuel power plant and a few solar panels. Tilos (Greece) has 500 residents and up to 2,000 visitors in summer. The electricity demand is met by a hybrid wind-PV battery station (1 MW), and by the interconnection with the energy systems of Kos (Greece) and Kalymnos (Greece). The Aran

Islands (Ireland) have 700 regular residents with an addition of 3,000 visitors during the summer. This island is connected to the mainland through a subsea cable. Currently, it imports electricity, thermal fuel, and transportation fuel. There are future plans to implement wind turbines (2.7 MW). Lastly, Salina (Italy) is a small touristic island with 2,500 residents that produces its electricity from fossil fuels generators.

The goal of this research is to explore to what extent an island's urban water cycle and the renewable electricity production system required to satisfy the urban water cycle's demand can become sustainable using Caye Chapel (Belize) as a study case. For this analysis, the water-energy system is defined as the island's urban water cycle and the renewable electricity system required to satisfy the urban water cycle's demand (see Figure 1). Their interactions are modeled to determine the different combinations of sources, technologies, and operational strategies that can lead to a sustainable water-energy system on the island. In this research, the sustainability of the water-energy system is represented by twelve indicators (see Table 2) that are used to measure the performance of the water-energy system, their economic and environmental aspects, and also to evaluate how sustainable the system can be. There are several challenges when it comes to using RES on an island. The first is the intermittent nature of RES like wind and solar. It produces variances in the power generation (Ellabban et al., 2014) that result in hourly electricity outputs that can be between 0 and the maximum power installed (Duić and da Graça Carvalho, 2004). A consequence of this intermittency is that the higher penetration of RES becomes limited (Duić et al., 2003). This occurs because most of the time, electricity generated by wind turbines and/or solar panels does not follow the load pattern of the grid (Duic et al., 2008; Duić et al., 2003). The mismatch imposes difficulties in matching energy supply with demands (Segurado et al., 2018). The second is that the water demand is time-dependent. The energy required for the water production and transport will have daily and monthly variances. Those demand patterns might not match with the energy production patterns (Segurado et al., 2018). The third, is the changeability of meteorological conditions like wind speed, solar irradiance, and precipitation. That introduces a challenge to operational planning. Finally, after integrating a model that simulates the interactions between renewable energy production and the water cycle's energy demand on an island, it needs to be tested, and its components must be designed in a way that guarantees the security of water supply and operational safety.

2. STUDY CASE

Caye Chapel is a small private island in Belize inside the Belize District, located in the Caribbean Sea, 26 km north-northeast of Belize City and 4.8 km south of Caye Caulker. Its coordinates are 17°41'45"N, 88°2'33"W (see Figure 2). It is surrounded by the UNESCO World Heritage designated Belize Barrier Reef ("Caye Chapel," 2021). Climate in Belize is moist tropical, with a dry season from November to April and a wet season from June to October. The mean annual temperature in Belize ranges from 23°C to 27°C (World Bank Group, 2021). Caye Chapel has an area of 114 hectares which houses a 9-hole golf course, named White Shark Golf Course, and a Four Seasons Hotel and Resort that will be opened in 2023 ("Thor Urbana - Proyecto Four Seasons Private Island & Resort Caye Chapel," n.d.). Apart from the golf course, it has a 10 slip marina and a private airstrip. Besides the hotel, it will have residential oceanfront lots, overwater bungalows, and Four Seasons branded private residences ("Thor Urbana - Proyecto Four Seasons Private Island & Resort Caye Chapel," n.d.). The maximum expected population is 3,313 inhabitants, from which 12% will be workers, 11% guests at the Four Seasons Hotel and Resort, 46% residents, people that live in the residences on the island, and 31% visitors, which are people that will not stay over the night (GFA Grupo Inmobiliario SC, personal communication, December 21, 2021).

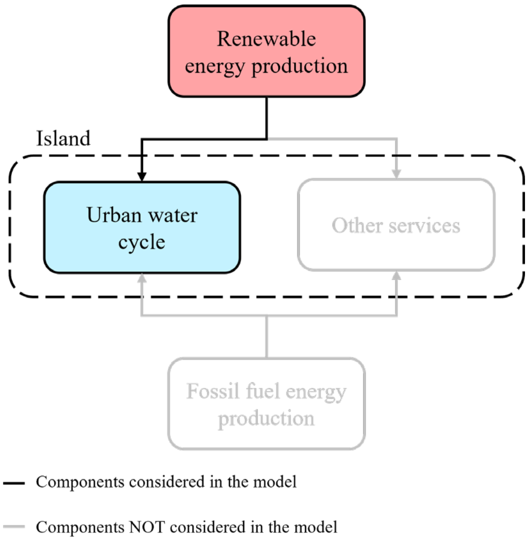


Figure 1. Boundaries of the water-energy system.

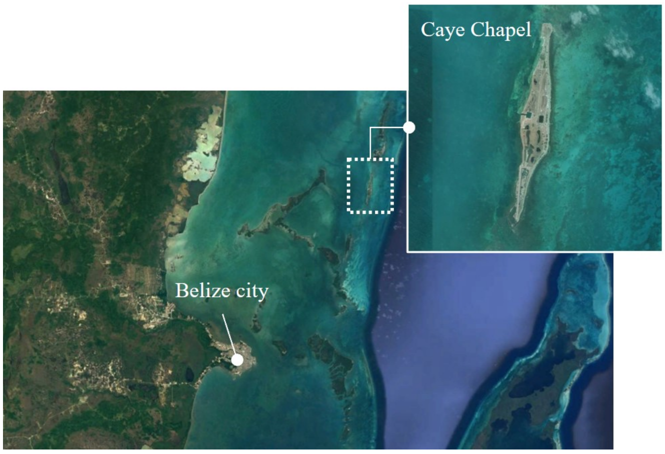


Figure 2. Geographical location of Caye Chapel. [source: Google earth pro V 7.3.4.8573. (May 16, 2022). Caye Chapel, Belize. 17°41'45"N, 88°2'33"W, eye alt 8.87 km. SIO, NOAA, U.S. Navy, GEBCO. Maxar Technologies 2022, CNES / Airbus 2022.]

According to GFA Grupo Inmobiliario SC (personal communication, June 9, 2022), the current design of the island considers a water system that produces potable water through a desalination facility that uses reverse osmosis (RO) to treat the water. The raw water is extracted from salty wells on the island. On top of that, some potable water is imported from the mainland on boats. The sanitary system is planned to treat the wastewater and transport it to the golf course's water bodies. The water bodies will serve as reservoirs for the rainwater captured on them during rainfall events and for the produced treated wastewater. It is considered that the stored water in the water bodies will be used to satisfy the irrigation demand. For the electricity system, liquified petroleum gas generators produce the electricity supply for the island. The island is not connected to the mainland's electricity grid.

3. METHODOLOGY

This section describes the methods and approach followed to determine which alternatives for the water-energy system are the most sustainable for Caye Chapel (see Figure 4). Twelve different alternatives are designed for the urban water cycle and renewable electricity production for Caye Chapel. Each alternative is modeled and optimized to minimize the water shortage, the treated water not reused, and renewable energy shortage. The twelve optimized alternatives are evaluated using Multi-Criteria Decision Analysis (MCDA) to define which one has the highest total value and will be considered optimal. Together, the optimization and evaluation process are oriented to determine which alternative is the most sustainable according to the indicators used in this research to represent "sustainability."

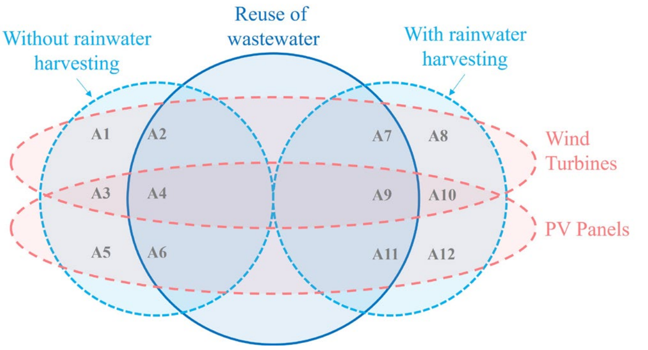


Figure 3. Diagram of the different alternatives for the water-energy system.

3.1. Design of the alternatives

In this research, twelve alternatives are designed for the water-energy system (consult Supplementary Material (SM) chapter 4). These alternatives are defined by combining different sources, technologies, and operational strategies. The elements that integrate the water-energy system are determined by using the methodology RenewIsland (consult SM section 4.1) which enables to assess the technical feasibility of various options for integrated energy and source planning on islands. It is based on four steps analysis approach: 1) mapping the island's need, 2) mapping the island resources, 3) devising scenarios with technologies that can use available resources to cover the needs, and 4) modelling the scenarios (Duic et al., 2008).

The alternatives for the water system are divided among those that consider the reuse of wastewater (or not) and those that consider rainwater harvesting (or not). For the energy system, the alternatives are divided by the type of renewable energy

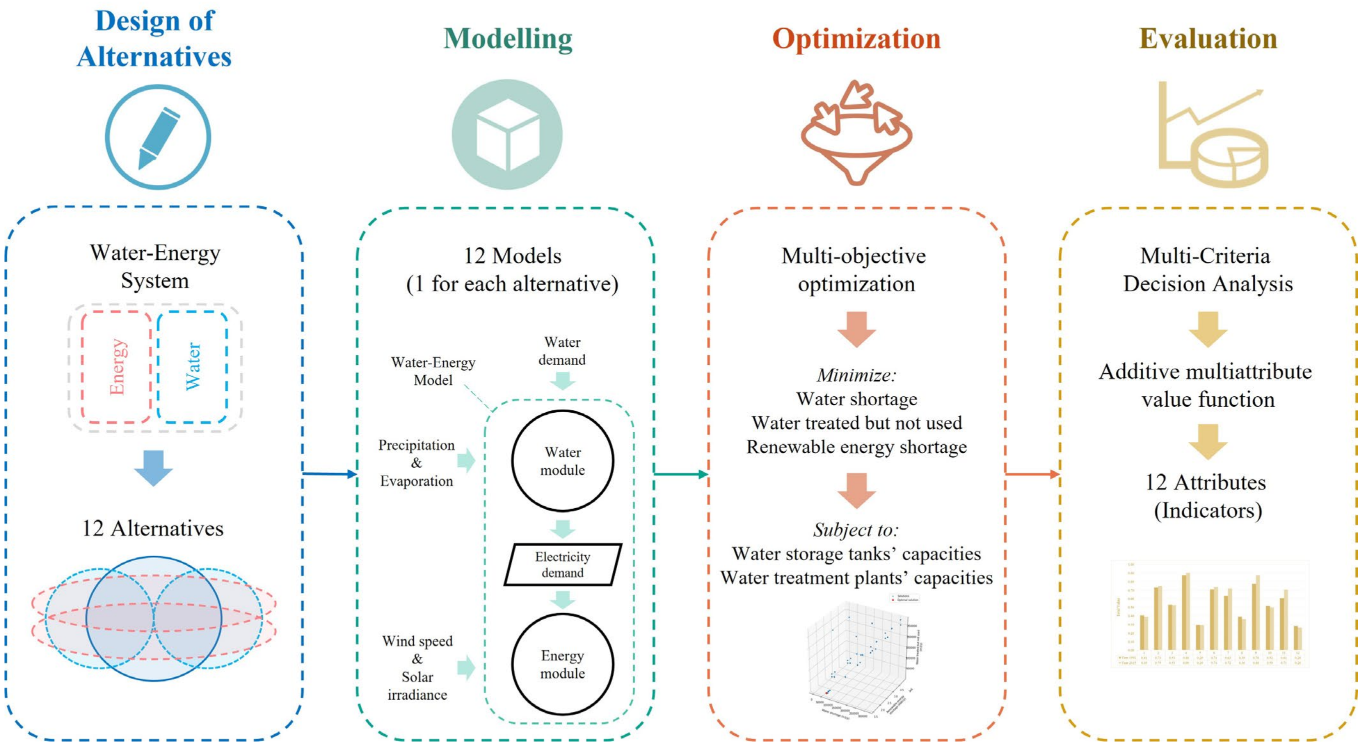


Figure 4. Diagram of the methodology.

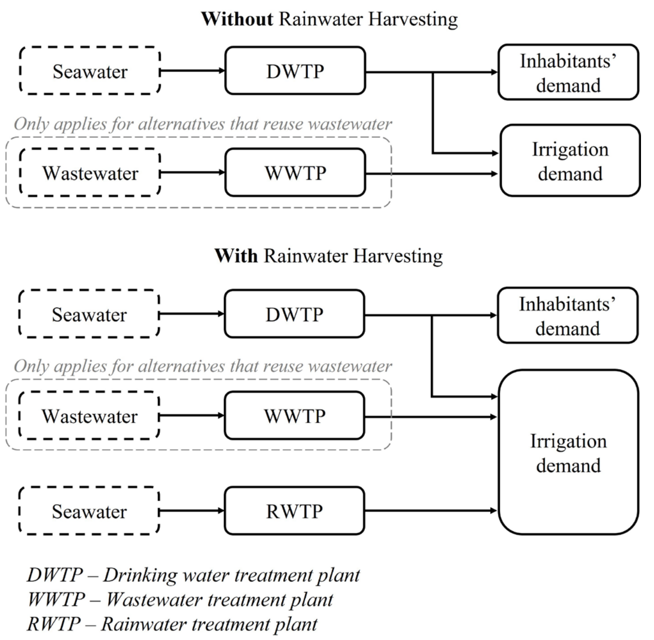


Figure 5. Diagram of alternatives with and without rainwater harvesting.

technology used for the electricity production. They can use wind turbines, PV panels, or both (see Figure 3). For example, from Figure 3 it is observed that alternative A10 do not reuse the treated wastewater, harvest the rainwater, and produce renewable electricity from wind turbines and PV panels. In this paper, the alternatives that harvest rainwater treat the rainwater that falls on the golf course's water bodies and use it for irrigation purposes (see Figure 5). The rainwater is not used for potable services because that would lead to higher investment and operational costs for the rainwater treatment plant. Furthermore, the rainwater treatment plant will operate intermittently during the year due to the periods where there is no precipitation. Each alternative has different elements that interact with each other. In Figure 6, it is observed that the elements that integrate the water system are the water storage tanks, water treatment facilities, and pumping stations (consult SM section 5.1). For all the alternatives, the raw water used to produce potable water is seawater. The potable water is produced by a drinking water treatment plant (DWTP) which is a desalination facility that uses RO to treat seawater. The potable water produced in the DWTP is transported to a drinking water storage tank (DWT). From the DWT the water can be distributed to the irrigation and recovery water storage tank (IWT) using the pumping station no. 1 and/or to the potable water services using the pumping station no. 2. On one side, the potable water that is transported to the IWT will be used to satisfy the irrigation demand. On the other side, the water supplied to the potable water services will serve to meet the inhabitants' demand. The wastewater that is produced by the potable water services will be conducted to the wastewater treatment plant (WWTP).

For the alternatives that do not consider the reuse of treated wastewater (A1, A3, A5, A8, A10, and A12), the treated wastewater will be discharged using pumping station no. 3 without receiving further use. For the alternatives that consider the reuse of treated wastewater (A2, A4, A6, A7, A9, and A11), the treated wastewater will be transported to the treated

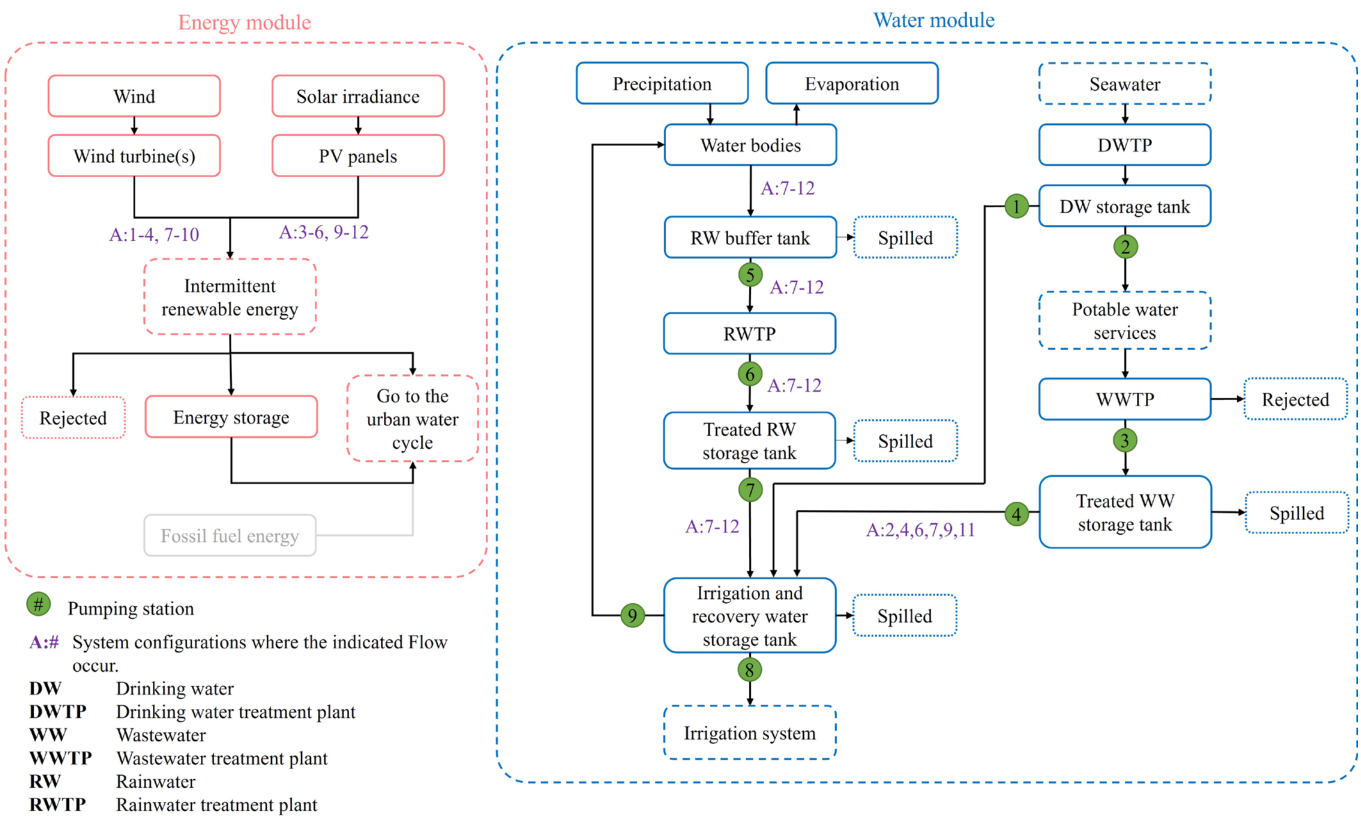


Figure 6. Water-energy system. Elements and their interactions for every alternative.

wastewater storage tank (WWT) using pumping station no. 3. Then, the treated wastewater will be transported to the IWT using pumping station no. 4.

It is observed in Figure 6 that all the alternatives for the water-energy system consider the golf course's water bodies (WB) and the IWT. The last supplies water to the irrigation system using pumping station no. 8 and to the WB using pumping station no. 9. The water supplied to the WB is used to keep the water levels at a certain height (consult SM section 5.1.8). For the alternatives that do not consider rainwater harvesting (A1 to A6), the water that overflows from the WB is discharged without further use. For the alternatives that consider rainwater harvesting (A7 to A12), the water that overflows from the WB is conducted to a rainwater buffer tank (RWB). Then, the rainwater is pumped with pumping station no. 5 into the rainwater treatment plant (RWTP). The rainwater is treated and stored in treated rainwater storage tank (RWT) using pumping station no. 6. Finally, the treated rainwater is pumped into the IWT using pumping station no. 7. Figure 6 shows that the alternatives that consider the reuse of treated wastewater and/or rainwater harvesting only use the treated water for irrigation purposes or as recovery water for the WB.

For the energy system, the elements considered are the renewable energy technologies for electricity production and storage (consult SM section 5.2). Depending on the alternative, the energy system may produce renewable electricity using only wind turbines, PV panels, or both. The electricity produced by these technologies can be distributed into the urban water cycle's grid, can be stored, or rejected. When the renewable electricity production and the stored energy are not sufficient to satisfy the hourly electricity demand from the urban water cycle, the electricity deficit is compensated with fossil energy sources.

3.2. Modeling

A model based simulation is designed for each alternative of the water-energy system of Caye Chapel which, for this research, is defined as the urban water cycle on the island and the renewable energy production system that is dedicated to produce electricity for the urban water cycle. The model designed for this research makes hourly time series balances between water and electricity demand, supply, and storage among its elements (consult SM chapter 5). It is based on the H2RES model design which also makes these balances but in addition to the model presented in this paper it considers heat and hydrogen balances (Krajačić et al., 2009; Lund et al., 2007) (consult SM Appendix 1). The model is composed of two modules, corresponding to the water system and the energy system, respectively. Each module has two types of input: hourly meteorological data, and hourly demand. The water module requires the precipitation and evaporation hourly data (consult SM section 5.1.1), and the hourly water demand for the inhabitants and irrigation (consult SM section 5.1.2). The energy module needs as input hourly data for the wind speed and/or solar irradiance (consult SM section 5.2.1), and the hourly electricity demand from the urban water cycle. The last is produced by the water module (see Figure 7).

3.2.1. Water Module

The elements in the water module are the water storage tanks, the water treatment facilities, and the pumping stations (consult SM section 5.1). For the water module, the model performs an hourly water balance on each element between the water that goes into them, the water that goes out of them, the water losses (only for the water bodies, wastewater treatment plant, and rainwater treatment plant), and the water stored (only for the water bodies and the water storage tanks). The module receives as input hourly data for the precipitation and evaporation, the irrigation water demand which is constant through the year, and the inhabitants' water demand which has hourly and monthly variations. The precipitation and evaporation input are required for all the alternatives, even those not considering rainwater harvesting. The reason is that the model performs water balances on the golf course's water bodies using the meteorological data. The average daily water demand is shown in Table 1. This research does not include the water demand for fire protection systems and heating, ventilation, and air conditioning (HVAC). The water losses considered in the system are localized in the potable water services (consult SM section 5.1.5) since not all the served water becomes wastewater, in the rainwater and wastewater treatment facilities water losses occur due to evaporation and sludge removal (consult SM section 5.1.5 and 5.1.10), and in the water bodies from the golf course due to evaporation.

Table 1. Caye Chapel's average daily water demand (source: GFA Grupo Inmobiliario SC, personal communication, December 9, 2021).

DESCRIPTION	PERCENTAGE	DEMAND (m^3/d)
Inhabitants' water demand	38%	1,413.58
Irrigation water demand	62%	2,333.00
Total	*100%*	*3,746.58*

For the water storage tanks, the model performs a lecture on the amount of water that is stored in the different tanks on every hourly time step. Then, based on that information, the model determines two things: the first, is how much water can go into each water storage tank. The second, is how much water can go out from each of them. The amount of water that flows between the different elements from the water module is restricted by the hourly capacity of the water treatment plants,

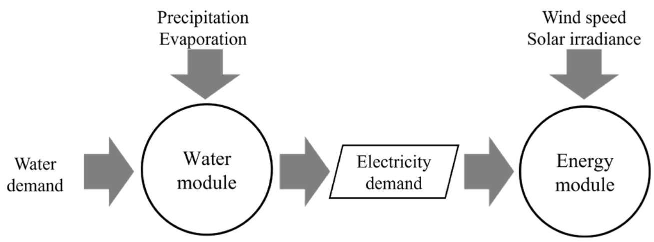


Figure 7. Scheme showing the input for the water and energy modules.

the capacity of the pumping stations, and the available storage capacity in the storage water tanks. The amount of water that go out from each storage tank is determined by the inhabitants' and/or irrigation water demand, the capacity of the corresponding pumping station, and the available water in each tank. For the cases were the water supplied to satisfy the inhabitants' and irrigation demand comes from the same water tank, the model gives preference to the inhabitants' water demand. After defining how much water goes in and out from each storage water tank, the model makes a water balance to define the initial stored water volumes for the next time step.

The water bodies from the golf course are modeled as a single water body with a constant area among its entire depth (consult SM section 5.1.8). The model decides how much water should go inside and outside the water bodies depending on the water level and the overflow level. The model will try to keep the water levels equal to the set level. In some cases, the water level can be higher than the set level due to precipitation. The model does not take any actions if the water level is higher than the set level and lower than the overflow level. The overflow level determines at which height the water bodies start to spill water. Then, at the beginning of every timestep, the model makes a water balance between the previous timestep inflow, previous time step outflow, current precipitation, and current evaporation. After that, it defines the water level and determines which decisions must be taken on how much water should be supplied into the water bodies or how much water must go out. The water demanded by the water bodies depends on the water level relative to the set level. However, the amount of water that goes into the water body is restricted by the pump capacity of the pumping station no. 9 and the available stored water from the irrigation water storage tank. Since the water used for the recovery of the water bodies and the irrigation system share the same water source (irrigation water tank), the model gives preference to the irrigation services (consult SM section 5.1.7). Further information about each element in the water module is provided in the SM, section 5.1.

3.2.2. Energy Module

For the energy module (consult SM section 5.2), the model makes an hourly energy balance between the electricity produced by the wind turbines and/or PV panels, the electricity demanded by the urban water cycle, and the energy stored and delivered by the energy storage technologies. It is assumed that the electricity demand from the water cycle that is not satisfied by renewable energies is satisfied by fossil energies. The model on every time step prioritizes the use of the generated electricity, then the use of energy stored, and finally the use of fossil energy. When the electricity produced by the renewable energy technologies exceeds the electricity demanded by the water system the exceedance of energy is stored in a lithium-ion battery (consult SM section 5.2.4), when there is available capacity in the battery, otherwise it is rejected. The hourly electricity demand for the urban water cycle depends on the amount of water treated by the water treatment facilities, and the operation of the pumping stations. The electricity consumption for each element of the water cycle is described in the SM chapter 5. Further information about each element in the energy module is provided in the SM, section 5.2.

3.3. Multi-objective optimization

The twelve alternatives are optimized using a Pareto-based multi-objective optimization. For this study, the sustainability of the water-energy system is represented by several indicators (see Table 2). Therefore, the optimization process is done by using three of the most relevant indicators, which are the water demand shortage, the water that is treated but not reused, and the renewable electricity shortage. The water-energy system is optimized by finding the optimal capacities for the water treatment facilities and water storage tanks. For this study, the optimal capacities for those two types of elements are those that produce the minimum water demand shortage, the minimum amount of treated water that is not reused, and the minimum renewable electricity shortage. The water demand shortage is an indicator for water security. The amount of treated that is not reused is an indicator of the efficiency of the water system. The ideal system would be the one that reuses all the water that treats. The renewable electricity shortage is an indicator for energy security and clean energy. In this process, it is used, as input for the model, 35 years of hourly data (from 1981 to 2015) for precipitation, evaporation, wind speed, and solar irradiance. The optimization is represented as follows:

minimize:

y_1 = mean water demand shortage (m^3/y)
y_2 = mean treated water that is not reused (m^3/y)
y_3 = mean renewable electricity shortage (kW/y)

subject to:

$x_1 \in (1800, 2800, 3800)$
$x_2 \in (100, 300, 500)$ *
$x_3 \in (50, 150, 250)$ **
$x_4 \in (100, 200, 300)$ **
$x_5 \in (1000, 2000, 3000)$
$x_6 \in (50, 150, 250)$
$x_7 \in (30, 60, 90)$ **
$x_8 \in (120, 170, 220)$

where:

x_1 = drinking water storage tank capacity (m^3)
x_2 = treated wastewater storage tank capacity (m^3)
x_3 = rainwater buffer tank capacity (m^3)
x_4 = treated rainwater storage tank capacity (m^3)
x_5 = irrigation and water bodies recovery tank capacity (m^3)
x_6 = wastewater treatment plant capacity (m^3/h)
x_7 = rainwater treatment plant capacity (m^3/h)
x_8 = drinking water treatment plant capacity (m^3/h)

* *Only applies for alternatives 2, 4, 6, 7, 9, and 11.*
** *Only applies for alternatives 7 to 12.*

(1)

The middle values for each parameter *(x)* are designed using the water-energy system's configuration from alternative A9 and the hourly meteorological data from year 1992, which corresponds to the year with the maximum yearly accumulated precipitation from the data set. The lower and higher end values for each parameter *(x)* are selected arbitrary for the optimization process (consult SM section 6.1).

The results of the multi-objective optimization process can be represented on a 3-dimensional plane (consult SM Appendix

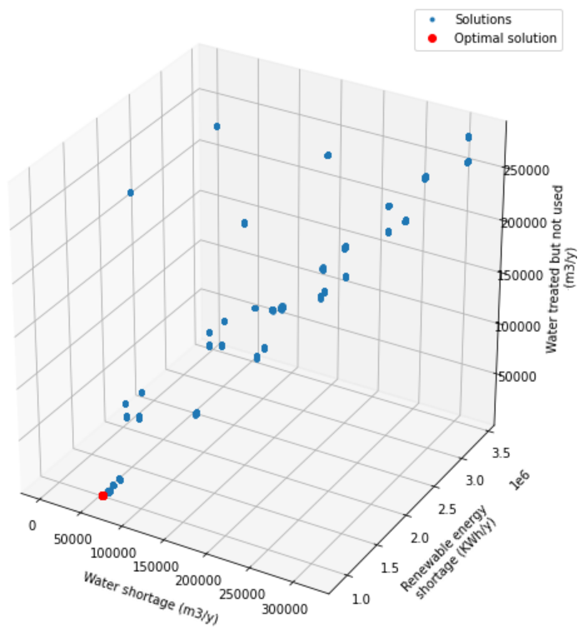


Figure 8. Results from the multi-objective optimization process for alternative A4.

IV), where each axis represents one of the optimization criteria (see Figure 8). As a result of the optimization process for one alternative, it is possible to obtain a cloud of dots that represent all the possible solutions or combinations for the capacities of the water treatment facilities and water storage tanks. More than one solution may produce the same outcome for the water demand shortage, the amount of treated water that is not reused, and the renewable electricity shortage. For those cases, the solution that is selected as optimal is the one that has the smallest capacities for the water treatment facilities and water storage tanks. The optimal solution for each alternative is defined as the closest one to the origin (0, 0, 0).

$$f(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8) = \text{minimize} \sqrt{{y_1}^2 + {y_3}^2 + {y_3}^2} \quad (2)$$

The optimized dimensions and capacities for the water storage tanks and water treatment facilities are shown in the SM section 6.2.

3.4. Evaluation with multi-criteria decision analysis

To determine which alternative is the most sustainable, the twelve optimized alternatives are evaluated using multi-criteria decision analysis. For this research, the additive multi-attribute value function is used to determine the total value of each alternative as a weighted sum of (individual) values per attribute (Eisenführ et al., 2010). In this case, the optimal alternative will be the one that gets the highest total value. The additive model determines the value $v(a)$ of an alternative a as

$$v(a) = \sum_{r=1}^{m} w_r v_r(a_r) \quad (3)$$

where $w_r > 0$ and

$$\sum_{r=1}^{m} w_r = 1 \quad (4)$$

As stated above a_r indicated the value of the attribute Xr for the alternative a, and $v_r(a_r)$ indicates the respective value of the attribute value function v_r. The w_r are attribute weights (Eisenführ et al., 2010).

In this study, the attributes (X) are the indicators (consult SM section 10.1). Three types of indicators are defined: performance, economic, and environmental (see Table 2). The performance indicators are based on the water and energy balances performed by the models. They describe the water and energy security aspects (i.e. water shortage and renewable energy shortage), functionality (i.e. percentage of time with water shortage, percentage of time with the water level from the water bodies below the set level, renewable energy production, and energy demand), and the efficiency of the system (i.e. water treated but not reused, renewable energy rejected, and average daily RES penetration). The economic indicators are an estimation of the investment that must be done to construct and operate the different elements from each alternative (consult SM chapter 7). Finally, the environmental indicator quantifies the greenhouse gases (GHG) emissions from the energy system.

For this research, the GHG emissions are quantified exclusively for the energy system (consult SM chapter 8). This research does not consider the GHG emissions from the chemical dosing for the operation and maintenance of the water treatment facilities. The reason is that these elements were proposed based on best practices only to estimate their electricity consumption from existing literature. For the wind turbines, PV panels, and the battery, the Life Cycle CO_2-eq emissions are estimated. For the fossil fuel, the operation GHG emissions are calculated assuming that the electricity is generated through processes that employ oil as the primary energy source. The GHG values used in this research are shown in Table 3.

Table 2. Indicators for performance, economic, and environmental aspects.

PERFORMANCE	WEIGHTS
For Water:	
Water shortage (m^3/month)	0.082
Percentage of time with water shortage (%)	0.091
Percentage of time with the water level from the water bodies below the set level (%)	0.018
Water treated but not reused (m^3/month)	0.100
For Energy:	
Renewable Energy production (MW/month)	0.027
Energy demand (MW/month)	0.073
Renewable energy shortage(MW/month)	0.118

Renewable energy rejected (MW/month)	0.109
Average daily RES penetration (%)	0.123
ECONOMIC	
Capital cost (M EUR)	0.069
O&M per year as a percentage of the capital cost (%)	0.064
ENVIRONMENTAL	
GHG emissions (10^3 kg CO_2-eq /year)	0.127

Table 3. Greenhouse gases (GHG) emissions.

ENERGY SOURCE	GHG EMISSIONS
Wind turbines	13 gCO_2-eq kW/h of electricity (Amponsah et al., 2014)
PV panels	91.1 gCO_2-eq kW/h of electricity (Amponsah et al., 2014)
Battery	74 gCO_2-eq per stored kWh of electricity (Peters et al., 2017)
Fossil energy (oil)	733 gCO_2-eq kW/h of electricity (Amponsah et al., 2014)

In this research, the weights (*w*) are defined using the swing method (Eisenführ et al., 2010) (consult SM section 10.2). More preference is given to environmental aspects such as RES penetration and treated water that is not reused, and less preference to economic aspects (see Table 2). The values a_r for each attribute or indicator (consult SM section 10.3) are obtained by running the model of every alternative using as an input the hourly meteorological data associated with the years with maximum (1992) and minimum (2015) yearly accumulated precipitation from the data set to see how each alternative performs under those conditions (see Table 4).

For each attribute *(X)* the attribute value function $v_r(a_r)$ is defined as a linear function (consult SM section 10.4). For the indicators where a high value of the attribute (a_r) represents a negative outcome, like the renewable energy shortage or capital cost, the attribute value function is:

$$v_r(a_r) = 1 - (a_r - a_{r,min})/(a_{r,max} - a_{r,min}) \quad (5)$$

Where $v_r(a_r)$ is in the interval [0, 1]. As shown above $a_{r,max}$ and $a_{r,min}$ are the maximum and minimum value, respectively, for the attribute among the different alternatives. For indicators where a higher value of the attribute *(ar)* indicates a better outcome, like the average daily RES penetration and the renewable energy production, the attribute value function is defined as:

$$v_r(a_r) = (a_r - a_{r,min})/(a_{r,max} - a_{r,min}) \quad (6)$$

4. RESULTS AND DISCUSSION

Table 4 shows the indicators' values from the optimized alternatives under two different scenarios that correspond to the years with maximum (1992) and minimum (2015) yearly accumulated precipitation. It is observed that the performance indicators for the water system have better values when the annual accumulated precipitation is higher, except for the water that is treated but not reused. The results indicate that the water shortage, the percentage of time with water shortage, and the percentage of time with the water level from the water bodies below the set level are better (smaller) under scenarios with more precipitation. For the alternatives with rainwater harvesting (A7 to A12), it is logical that the water shortage becomes smaller as the rainwater availability becomes higher because the water system will have more raw water to satisfy the irrigation demand. However, this effect also occurs with the alternatives that do not consider rainwater as a source (A1 to A6). One reason could be that the model considers the hourly irrigation water demand as 0 when the hourly precipitation is equal to or higher than 1 mm/hr (consult SM section 5.1.7). The model assumes that the precipitation satisfies the irrigation demand during those periods. Consequently, the scenario with higher precipitation (1992) is more likely to demand less water for irrigation purposes.

The indicator for the treated but not reused water shows the worst values for the scenario with higher precipitation (1992) for the alternatives that reuse wastewater and consider rainwater harvesting (A7, A9, and A11). This suggests that the system could be improved to become more efficient to reduce the amount of water that is treated but not reused. Therefore, it is possible that the water shortage could be reduced as well. The performance indicators' values for the energy system (see Table 4) show similar behavior between the two years, except for the rejected renewable energy on alternatives A5, A6, A11, and A12. All these alternatives use solar energy as their only renewable source for electricity production. It is observed that for those alternatives, less renewable energy is rejected under scenarios with higher precipitation. It is expected that during rainy days the solar irradiance will be reduced; therefore, less electricity is produced, and consequently, less renewable electricity is rejected. However, the rejected energy for these alternatives is too small compared to other alternatives. It could be the expected rejected energy for an average system and not a specific trend for systems that use PV panels for electricity production and perform under rainy conditions.

The economic indicators do not change for both scenarios. The operation and maintenance (O&M) costs were estimated per year without considering meteorological conditions. The costs for the elements from the water system are estimated using the CoP cost calculator (Royal HaskoningDHV, 2022) and the costs for the elements from the energy system are estimated

Table 4 . Indicators' values for each optimized alternative under two different scenarios.

SCENARIO YEAR 1992

ALTERNNATIVE	1	2	3	4	5	6	7	8	9	10	11	12
Reuse of wastewater	✓	✓	×	✓	×	✓	✓	×	✓	×	✓	×
Rainwater harvesting	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓
Wind turbines	✓	✓	✓	✓	×	×	✓	✓	✓	✓	×	×
PV panels	×	×	✓	✓	✓	✓	×	×	✓	✓	✓	✓
PERFORMANCE												
For Water:												
Water shortage (m^3/month)	11,981.32	3,068.46	11,981.32	3,068.46	11,981.32	3,068.46	3,005.32	10,967.20	3,005.32	11,029.14	3,005.32	11,029.14
Percentage of time with water shortage (%)	32%	12%	32%	12%	32%	12%	11%	30%	11%	30%	11%	30%
Percentage of time with the water level from the water bodies below the minimum level (%)	43%	31%	43%	31%	43%	31%	31%	43%	31%	43%	31%	43%
Water treated but not reused (m^3/month)	0	379	0	379	0	379	1,388	103	1,388	11	1,388	11
For Energy:												
Renewable Energy production (MW/month)	1,166	1,166	761	761	312	312	1,166	1,166	761	761	312	312
Energy demand (MW/month)	715	520	715	520	715	520	522	717	522	717	522	717
Renewable energy shortage(MW/month)	251	154	195	92	411	240	155	252	93	197	242	413
Renewable energy rejected (MW/month)	694	792	235	325	4	24	791	694	325	234	24	4
Average daily RES penetration (%):	65%	71%	73%	82%	39%	50%	71%	65%	82%	72%	50%	39%
ECONOMIC												
Capital cost (EUR x10^3)	33,813.26	33,568.31	28,718.57	28,473.62	23,307.55	23,062.59	36,086.96	36,154.23	30,992.27	30,960.75	25,581.25	25,549.73
O&M per year as a percentage of the capital cost (%)	3.54%	3.34%	3.69%	3.45%	3.93%	3.64%	3.51%	3.70%	3.64%	3.86%	3.85%	4.13%
ENVIRONMENTAL												
GHG emissions (10^3 kg CO_2-eq /year)	2,455.79	1,600.93	2,062.89	1,150.33	3,999.57	2,514.30	1,609.11	2,466.16	1,158.91	2,074.20	2,527.88	4,015.00

SCENARIO YEAR 2015

ALTERNNATIVE	1	2	3	4	5	6	7	8	9	10	11	12
PERFORMANCE												
For Water:												
Water shortage (m^3/month)	12,183.82	3,958.81	12,183.82	3,958.81	12,183.82	3,958.81	3,958.81	12,183.82	3,958.81	12,183.82	3,958.81	12,183.82
Percentage of time with water shortage (%)	33%	15%	33%	15%	33%	15%	15%	33%	15%	33%	15%	33%
Percentage of time with the water level from the water bodies below the minimum level (%)	63%	45%	63%	45%	63%	45%	45%	63%	45%	63%	45%	63%
Water treated but not reused (m^3/month)	0	0	0	0	0	0	0	0	0	0	0	0
For Energy:												
Renewable Energy production (MW/month)	1,166	1,166	780	780	346	346	1,166	1,166	780	780	346	346
Energy demand (MW/month)	715	521	715	521	715	521	521	715	521	715	521	715
Renewable energy shortage(MW/month)	251	154	186	86	387	226	154	251	86	186	226	387
Renewable energy rejected (MW/month)	694	792	244	339	11	43	792	694	339	244	43	11
Average daily RES penetration (%):	65%	71%	74%	83%	42%	54%	71%	65%	83%	74%	54%	42%
ECONOMIC												
Capital cost (EUR x10^3)	33,813.26	33,568.31	28,718.57	28,473.62	23,307.55	23,062.59	36,086.96	36,154.23	30,992.27	30,960.75	25,581.25	25,549.73
O&M per year as a percentage of the capital cost (%)	3.54%	3.34%	3.69%	3.45%	3.93%	3.64%	3.51%	3.70%	3.64%	3.86%	3.85%	4.13%
ENVIRONMENTAL												
GHG emissions (10^3 kg CO_2-eq /year)	2,457.55	1,602.77	2,004.16	1,122.07	3,827.02	2,435.34	1,602.77	2,457.55	1,122.07	2,004.16	2,435.34	3,827.02

from the Technology data catalogues from the Danish Energy Agency (Technology Data: Energy Storage, 2018; Technology Data: Generation of Electricity and District Heating, 2016) (consult SM chapter 7). Lastly, the indicator for GHG emissions between the two scenarios is not that sensitive to changes in the amount of yearly precipitation.

The electricity demand from the urban water cycle's and other services is 755.81 ± 103.94 MW/month, depending on the

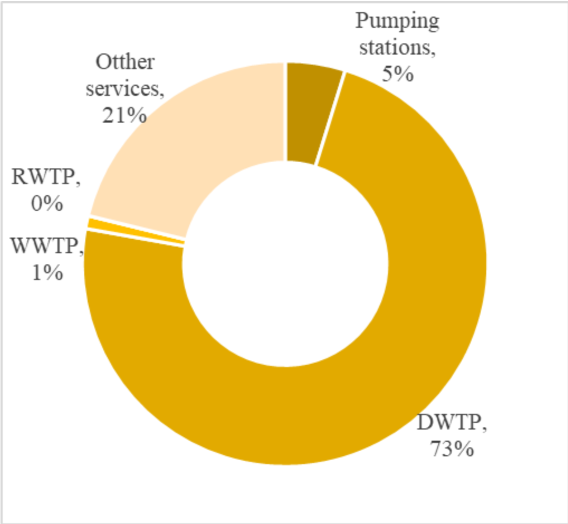


Figure 9. Percentages for the monthly average electricity consumption from the elements in the water cycle and other services (using a sample of 35 years).

alternative (consult SM chapter 9). The other services represent the electricity consumption from the different buildings and amenities on the island, excluding HVAC systems and machinery rooms. These services are not integrated into the model since they are out of the scope of this research. The urban water cycles' electricity demand represents 77.36 ± 3.11 % (587.69 ± 103.94 MW/month) of the island's electricity demand. The other service's electricity demand represents the remaining 22.64 ± 3.11% (168.12 MW/month) (GFA Grupo Inmobiliario SC, personal communication, December 9, 2021) (consult SM Appendix VI). Figure 9 shows the monthly average percentage of electricity consumption (using 35 years) for the elements in the urban water cycle and other services.

Figure 10 shows the daily average RES penetration for the urban water cycle on each alternative for the year with maximum (1992) and minimum (2015) yearly accumulated precipitation. The RES penetration refers to the percentage of electricity generated by RES relative to the amount of

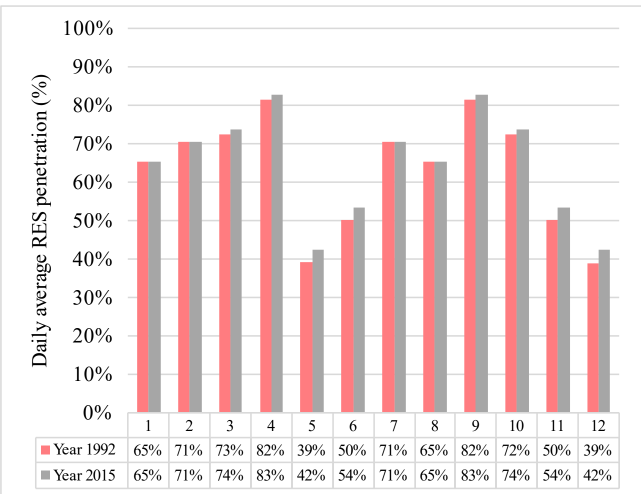
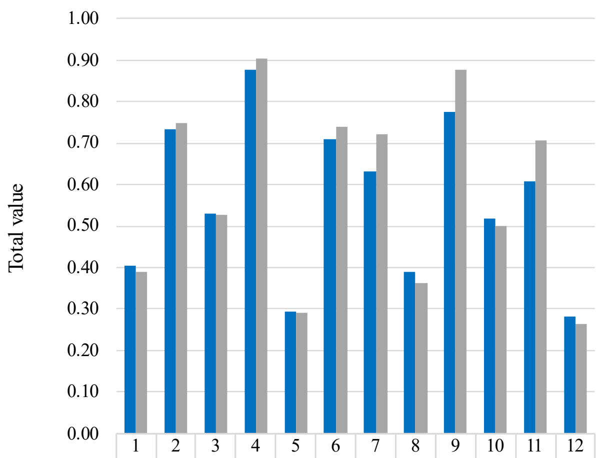


Figure 10. Daily average RES penetration on the urban water cycle for each alternative for the year 1992.

electricity consumed by the urban water cycle. The results indicate that the alternatives with the highest RES penetration are A4 and A9. Both have a daily average penetration higher than 80% for the two years. The alternatives with the worst percentages are A5 and A12, which are below 40%. It is observed that the alternatives have the same percentages for RES penetration when they share the same characteristics for reusing or not the wastewater and for the type and number of renewable energy sources. For example, alternatives A1 and A8 have the same values for RES penetration and both reuse wastewater and use wind turbines for electricity generation. This analysis shows that changing between alternatives with or without rainwater harvesting does not produce significant changes (less than 1%, see Table 4) in the daily average RES penetration. The results show that the alternatives that use the same renewable energy source but different criteria for the reuse of wastewater, for example, A1 and A2, present RES penetration variations between 6% and 11%. The alternatives that consider the reuse of wastewater (A2, A4, A6, A7, A9, and A11) present higher percentages for RES penetration if they are compared to their counterparts that do not reuse wastewater. It is observed that the most significant variations in the RES penetration occur when there is a change in the type of renewable energy source. For example, alternatives A2, A4, and A6 consider the reuse of wastewater but differ in the type of renewable energy source. Alternative A2 uses wind turbines and has a daily average RES penetration of 71%, A4 uses wind turbines and PV panels with 82%, and A6 only uses PV panels with a 50% RES penetration. The highest penetration is achieved by the alternatives that use wind turbines combined with PV panels, and the smallest for those alternatives that only consider PV panels. Then, it is observed that the most significant changes in the RES penetration can be conducted by modifying the elements from the energy system and not the operational strategies or water sources from the water system.

The RES penetration values can be further improved if the elements in the energy system are co-optimized, for example, the dimension of the batteries, wind turbines, and PV panels capacities. In addition, it can be improved if the operational hours and capacity of the desalination facility are optimized to match the optimal periods of renewable electricity production. The desalination facility is recommended for this process because it is the element that consumes the highest fraction of the electricity load (see Figure 9).

Figure 11 shows the results from the multi-attribute value function. Each alternative is evaluated under two different scenarios corresponding to the years 1992 and 2015. In Figure 11, the outperformed alternatives are A1, A5, A8, and A12. All of them share two characteristics: the first is that they do not consider the reuse of treated wastewater and the second, that they use only one type of renewable energy source, either wind or solar. These alternatives have the lowest scores for treated but not reused water. This is because they do not consider the reuse of wastewater. In addition, alternatives A5 and A12 have lower scores for CO_2-eq emissions. This is because renewable energy shortage is the highest for these two alternatives meaning that more fossil energy is required to satisfy the urban water cycle's electricity demand.



	1	2	3	4	5	6	7	8	9	10	11	12
Year 1992	0.41	0.73	0.53	0.88	0.29	0.71	0.63	0.39	0.78	0.52	0.61	0.28
Year 2015	0.39	0.75	0.53	0.90	0.29	0.74	0.72	0.36	0.88	0.50	0.71	0.26

Figure 11. Total values obtained from the MCDA for each alternative.

The optimal alternatives are A4 and A9. These two alternatives share two characteristics: the first, that they consider the reuse of wastewater and the second, that they use wind and solar as renewable energy sources. Alternative A4 has the highest total values for both years, demonstrating that it is the optimal alternative for Caye Chapel, meaning that it is the most sustainable alternative for the water-energy system. Under these scenarios, this alternative produces the lowest values for electricity demand from the urban water cycle, renewable energy shortage, CO_2-eq emissions, and the maximum renewable energy penetration. It also produces the smallest water demand shortage from all the alternatives that consider the reuse of wastewater (see Table 4). Then, it is observed that the optimal alternative for the water-energy system is the one that includes the reuse of wastewater in its design and the use of multiple renewable energy sources.

For this research, more importance is given (higher weights) to the indicators that are related to water and energy security and environmental aspects, and less relevance is given to economic aspects. However, this is not always true for decision-makers. Sometimes economic factors play a more important role in the rational decision-making process. Figure 12 shows what would be the results of increasing the attribute weight given to the capital cost for the outperformed (A1, A5, A8, and A12) and most optimal (A4 and A9) alternatives in the scenario with the highest yearly accumulated precipitation. It is observed that the most outperformed alternatives A5 and A12 become more attractive as the weight of the capital cost increases. Contrary to that, the optimal alternatives A4 and A9 become less attractive when the decision-maker gives more importance to the capital cost. This analysis indicates that the capital cost's weight needs to be higher that 0.75 to change the outcome of the MCDA. In that way, alternatives A5 and A12 would become more attractive than A4 and A9 (consult SM section 10.6).

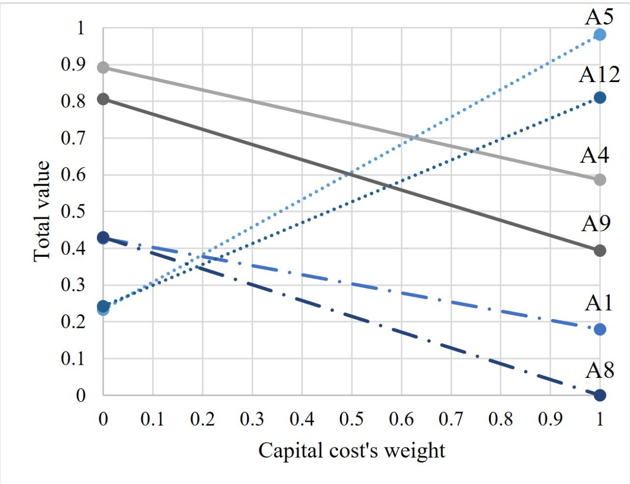


Figure 12. Sensitivity analysis for the weight of the attribute "Capital cost".

5. CONCLUSIONS

The aim of this paper is to explore to what extent an island's urban water cycle and the renewable electricity production system required to satisfy the urban water cycle's demand can become sustainable using Caye Chapel (Belize) as a study case. In this research, the water-energy system is defined as the renewable electricity system and the urban water cycle of the island. Several indicators are proposed to represent the sustainability of the water-energy system. Twelve alternatives are generated for the water-energy system. Those alternatives are modeled and optimized using a Pareto based multi-objective optimization to produce the minimum water demand shortage, amount of water that is treated but not reused, and renewable electricity shortage. Then, the optimized alternatives are evaluated using MCDA, and the best (more sustainable) alternative is determined with the additive multi-attribute value function. In the case study, the RES penetration is affected the most by the type of renewable energy source. Higher penetrations were obtained for alternatives that consider the use of wind turbines and solar panels, and the lowest values for those that only consider PV panels. It was shown that considering the reuse of wastewater as an operational strategy increases the RES penetration. It was observed that harvesting or not the rainwater does not affect the RES penetration. The results from the MCDA show that the dominant alternatives were A4 and A9, which consider the reuse of wastewater and use as renewable energy sources, both wind and solar, while the dominated solutions A1, A5, A8, and A12 were those that make use of only one type of renewable energy source and do not consider the reuse of wastewater. However, it was shown that if the decision-maker assigns more weight to each alternative's capital cost, the alternatives A5 and A12 could become more attractive than alternatives A4 and A9.

6. RECOMMENDATIONS

This research only considers the interaction between the renewable energy production system and the urban water cycle. Further improvements must be made to integrate the entire island's electricity consumption and include the water demand for the HVAC and fire protection systems. It was shown that giving more importance to the capital cost in the MCDA can make the best and worst alternatives exchange places. It is recommended to include the economic aspects of each alternative in the optimization process and to use more than three values per element (x_1, x_2, …, x_8). For example, evaluate five values per element by adding two more values between the existing ones. Keeping the same difference in magnitude between the extremes and the middle value. This would provide a more detailed shape of the Pareto front. On top of that, it is advised to include the energy costs during the optimization process. The optimization process can also be improved by co-optimizing the elements from the energy system, like the capacities for the battery, wind turbines, and PV panels. Furthermore, optimization of the operational hours of the desalination facility could be done to match the periods with optimal renewable electricity production and balance the renewable resources. However, these actions may demand more computational time and capacity.

The urban water cycle simulated in this research only collects the rainwater that falls on the surface of the golf course's water bodies. This aspect can be improved by considering additional surfaces for rainwater collection, for example, impervious areas such as squares and roofs. The different alternatives are modeled with the same capacities for the different pumping stations. For example, pumping station no. 1 has the same capacity for every alternative. Further improvements to the model can include the design of every pumping station for each alternative. The indicators determined for this research only include the percentage of time when the water shortage occurs. It is recommended to include the percentage of water shortage as an indicator relative to the demand. This indicator would provide a better insight into the severity of the shortage. Finally, the model in the water module is designed to prioritize the inhabitant's water demand over the irrigation demand. This is done by restricting the amount of water that goes out from the drinking water storage tanks. When the water volume inside the tank is lower than 50% of its total capacity, no water is delivered for irrigation purposes. This represents a problem during the optimization process because, for bigger water tanks, more water is required to fill the tank above 50% of its capacity and therefore be able to supply water for irrigation purposes. Using a specific volume for the constraint is recommended instead of a percentage of the total volume. The same problem occurs with the irrigation and recovery water storage tank.

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REFERENCES

Amponsah, N.Y., Troldborg, M., Kington, B., Aalders, I., Hough, R.L., 2014. Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. Renewable and Sustainable Energy Reviews 39, 461–475. https://doi.org/10.1016/j.rser.2014.07.087

Bağcı, B., 2009. Towards a Zero Energy Island. Renewable Energy 34, 784–789. https://doi.org/10.1016/j.renene.2008.04.027

Cabrera, P., Carta, J.A., Lund, H., Thellufsen, J.Z., 2021. Large-scale optimal integration of wind and solar photovoltaic power in water-energy systems on islands. Energy Conversion and Management 235, 113982. https://doi.org/10.1016/j.enconman.2021.113982

Calise, F., Cappiello, F.L., Vicidomini, M., Petrakopoulou-Robinson, F., 2020. Water-energy nexus: A thermoeconomic analysis of polygeneration systems for small Mediterranean islands. Energy Conversion and Management 220, 113043. https://doi.org/10.1016/j.enconman.2020.113043

Caye Chapel, 2021. . Wikipedia. URL https://en.wikipedia.org/w/index.php?title=Caye_Chapel&oldid=1025655725 (accessed 3.10.22).

Duić, N., da Graça Carvalho, M., 2004. Increasing renewable energy sources in island energy supply: case study Porto Santo. Renewable and Sustainable Energy Reviews 8, 383–399. https://doi.org/10.1016/j.rser.2003.11.004

Duic, N., Krajacic, G., Dagracacarvalho, M., 2008. RenewIslands methodology for sustainable energy and resource planning for islands. Renewable and Sustainable Energy Reviews 12, 1032–1062. https://doi.org/10.1016/j.rser.2006.10.015

Duić, N., Lerer, M., Carvalho, M.G., 2003. Increasing the supply of renewable energy sources in island energy systems. International Journal of Sustainable Energy 23, 177–186. https://doi.org/10.1080/01425910412331290760

Eisenführ, F., Weber, M., Langer, T., 2010. Rational Decision Making. Springer, Berlin.

Ellabban, O., Abu-Rub, H., Blaabjerg, F., 2014. Renewable energy resources: Current status, future prospects and their enabling technology. Renewable and Sustainable Energy Reviews 39, 748–764. https://doi.org/10.1016/j.rser.2014.07.113

Euopean Comission, 2022. Clean energy for EU islands. URL https://clean-energy-islands.ec.europa.eu/islands (accessed 6.12.22).

Hamiche, A.M., Stambouli, A.B., Flazi, S., 2016. A review of the water-energy nexus. Renewable and Sustainable Energy Reviews 65, 319–331. https://doi.org/10.1016/j.rser.2016.07.020

Kougias, I., Bódis, K., Jäger-Waldau, A., Moner-Girona, M., Monforti-Ferrario, F., Ossenbrink, H., Szabó, S., 2016. The potential of water infrastructure to accommodate solar PV systems in Mediterranean islands. Solar Energy 136, 174–182. https://doi.org/10.1016/j.solener.2016.07.003

Krajačić, G., Duić, N., Carvalho, M. da G., 2009. H2RES, Energy planning tool for island energy systems – The case of the Island of Mljet☆. International Journal of Hydrogen Energy 34, 7015–7026. https://doi.org/10.1016/j.ijhydene.2008.12.054

Lund, H., Duić, N., Krajacˇić, G., Graça Carvalho, M. da, 2007. Two energy system analysis models: A comparison of methodologies and results. Energy 32, 948–954. https://doi.org/10.1016/j.energy.2006.10.014

Melián-Martel, N., del Río-Gamero, B., Schallenberg-Rodríguez, J., 2021. Water cycle driven only by wind energy surplus: Towards 100% renewable energy islands. Desalination 515, 115216. https://doi.org/10.1016/j.desal.2021.115216

Ntziachristos, L., Kouridis, C., Samaras, Z., Pattas, K., 2005. A wind-power fuel-cell hybrid system study on the non-interconnected Aegean islands grid. Renewable Energy 30, 1471–1487. https://doi.org/10.1016/j.renene.2004.11.007

Olsson, G., 2013. Water, energy and food interactions—Challenges and opportunities. Front. Environ. Sci. Eng. 7, 787–793. https://doi.org/10.1007/s11783-013-0526-z

Papathanassiou, S.A., Boulaxis, N.G., 2006. Power limitations and energy yield evaluation for wind farms operating in island systems. Renewable Energy 31, 457–479. https://doi.org/10.1016/j.renene.2005.04.002

Parissis, O.-S., Zoulias, E., Stamatakis, E., Sioulas, K., Alves, L., Martins, R., Tsikalakis, A., Hatziargyriou, N., Caralis, G., Zervos, A., 2011. Integration of wind and hydrogen technologies in the power system of Corvo island, Azores: A cost-benefit analysis. International Journal of Hydrogen Energy 36, 8143–8151. https://doi.org/10.1016/j.ijhydene.2010.12.074

Peters, J.F., Baumann, M., Zimmermann, B., Braun, J., Weil, M., 2017. The environmental impact of Li-Ion batteries and the role of key parameters – A review. Renewable and Sustainable Energy Reviews 67, 491–506. https://doi.org/10.1016/j.rser.2016.08.039

Royal HaskoningDHV, 2022. CoP Kostencalculator drinkwater. Royal HaskoningDHV, Netherlands.

Segurado, R., Costa, M., Duić, N., 2018. Integrated Planning of Energy and Water Supply in Islands, in: Renewable Energy Powered Desalination Handbook. Elsevier, pp. 331–374. https://doi.org/10.1016/B978-0-12-815244-7.00009-X

Segurado, R., Costa, M., Duić, N., Carvalho, M.G., 2015. Integrated analysis of energy and water supply in islands. Case study of S. Vicente, Cape Verde. Energy 92, 639–648. https://doi.org/10.1016/j.energy.2015.02.013

Spyrou, I.D., Anagnostopoulos, J.S., 2010. Design study of a stand-alone desalination system powered by renewable energy sources and a pumped storage unit. Desalination 257, 137–149. https://doi.org/10.1016/j.desal.2010.02.033

Technology Data: Energy Storage, 2018. . Energistyrelsen Danish Energy Agency and Energinet.

Technology Data: Generation of Electricity and District Heating, 2016. . Energistyrelsen Danish Energy Agency and Energinet.

Thor Urbana - Proyecto Four Seasons Private Island & Resort Caye Chapel, n.d. . Thor Urbana. URL https://www.thorurbana.com/proyecto/caye-chapel (accessed 12.1.21).

Triantafyllou, P., Koroneos, C., Kondili, E., Kollas, P., Zafirakis, D., Ktenidis, P., Kaldellis, J.K., 2021. Optimum green energy solution to address the remote islands' water-energy nexus: the case study of Nisyros island. Heliyon 7, e07838. https://doi.org/10.1016/j.heliyon.2021.e07838

Ulleberg, Ø., Nakken, T., Eté, A., 2010. The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools. International Journal of Hydrogen Energy 35, 1841–1852. https://doi.org/10.1016/j.ijhydene.2009.10.077

United Nations, Division for Sustainable Development, 2010. Trends in sustainable development. United Nations, New York.

World Bank Group, 2021. World Bank Climate Change Knowledge Portal: Belize. URL https://climateknowledgeportal.worldbank.org/ (accessed 6.14.22).