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Managing Water and Energy on Small Islands Study Case Caye Chapel

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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. In this paper, models for an energy generation system and the processes in the urban water cycle are formulated. These are combined and then used to determine optimal parameters for 12 different possible alternatives in two scenarios.

Keywords: Urban water cycle; Renewable energy; Water-energy nexus; 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 2 of the 17 Sustainable Development Goals (SDGs) from the 2030 Agenda for Sustainable Development, presented in 2015. Unfortunately, the security of water and energy is being threatened by climate change (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).

The goal of this research is to explore to what extent an island can become sustainable in terms of water and energy using Caye Chapel (Belize) as a study case. For this analysis the water-energy system is defined as the renewable electricity system and the urban water cycle of the island. Their interactions are modeled to determine the different combinations of technologies and operational strategies that can lead to a sustainable water-energy system on the island. The water-energy system is limited to the urban water cycle and renewable energy production exclusively for the urban water cycle as shown in Figure 1. Nevertheless, there are several challenges when it comes to using renewable energy sources (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

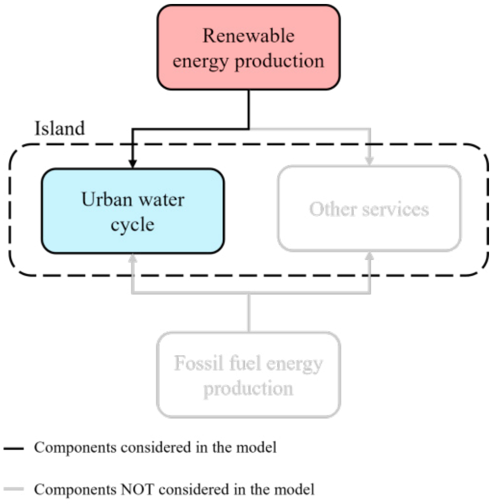

Figure 1. Boundaries of the water-energy system.

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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. It is surrounded by the UNESCO World Heritage designated Belize Barrier Reef ("Caye Chapel," 2021). Climate in Belize is subtropical, with a dry season from February to May and a wet season from June to November, with an interruption from August to September. The mean temperature in Belize District is 24.7°C in December and 28.4°C in July. 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, and 31% visitors, which are people that will not stay over the night.

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. We designed twelve different alternatives 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 alternative is the best.

3.1. Design of the alternatives

In this research, we designed twelve alternatives for the water-energy system. These alternatives are defined by combining different sources, technologies, and operational strategies (see Figure 3). For example, alternative A10 has decentralized water production, does not reuse treated wastewater, and the production of renewable electricity comes from wind turbines

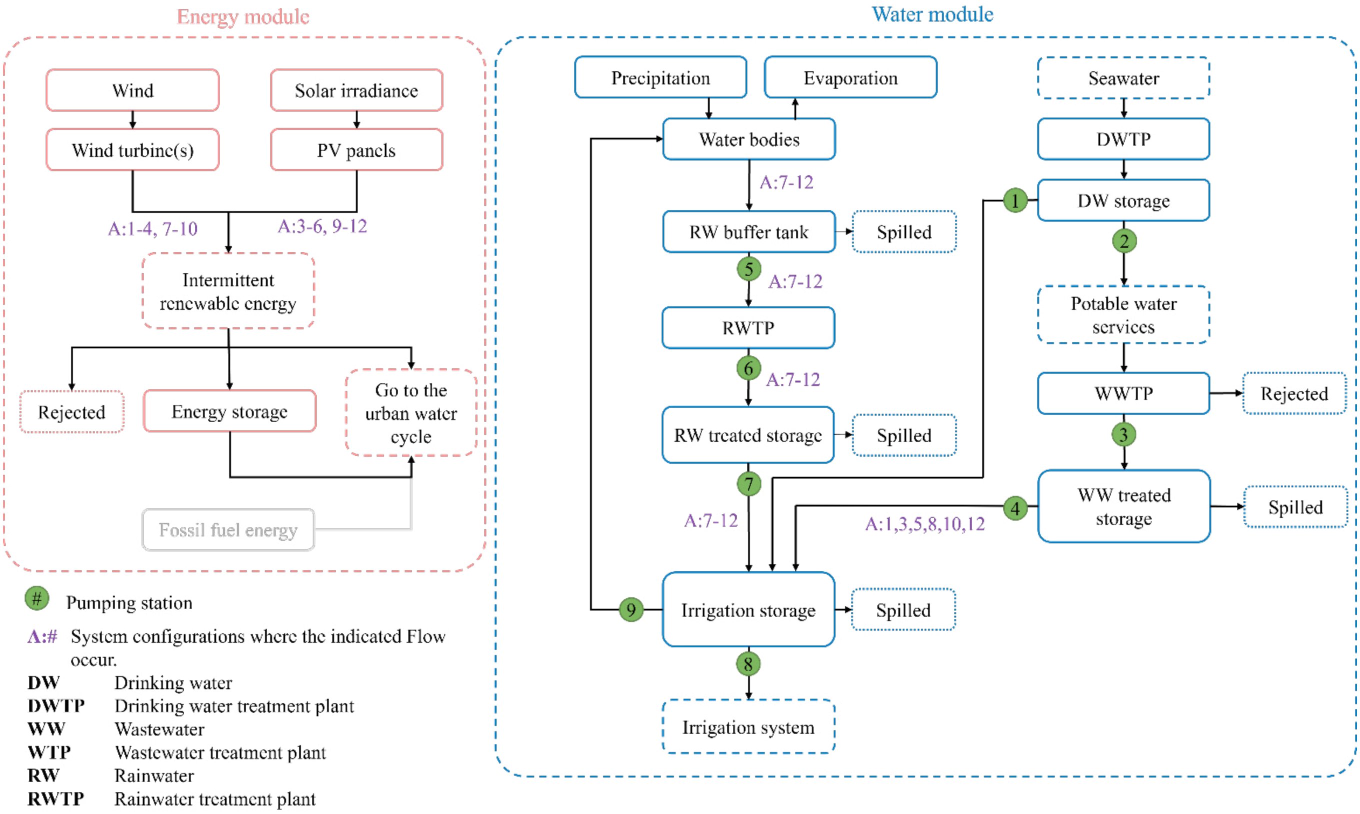


Figure 2. Water-energy system. Elements and their interactions for every configuration.

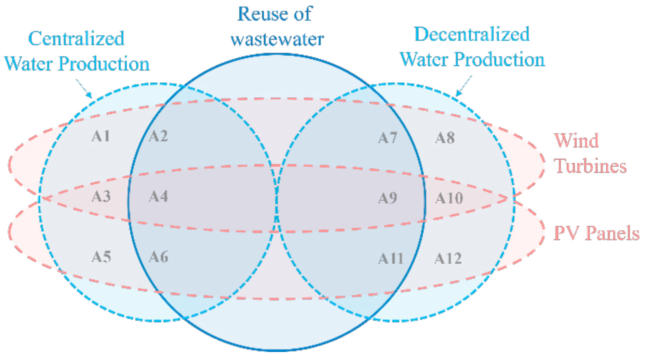


Figure 3. Diagram of the different alternatives for the water-energy system.

and PV panels. In this paper, Decentralized Water Production means that the water employed to satisfy the island's water demand comes from two sources: rainwater and seawater. While Centralized Water Production means that the water employed to satisfy the island's water demand comes only from seawater. Each alternative has different elements that interact with each other (see Figure 2). In the water system, these elements are the water treatment facilities, water storage tanks, water bodies from the golf course, and pumping stations. For the energy system, we consider as elements the renewable energy technologies for electricity production and storage. We determine the elements from each alternative by using the methodology RenewIsland which enables us to assess the technical feasibility of various options for integrated energy and source planning on islands (Duic et al., 2008).

3.2. Modeling

We design a model-based simulation 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 producing 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. It is based on the H2RES model design (Krajačić et al., 2009; Lund et al., 2007). The model is composed of two modules, corresponding to the water system and the energy system, respectively. For the water module, the model performs an hourly water balance on each element between the influent, effluent, water losses, and water stored. The water losses only apply for the water treatment processes and for the water bodies due to evaporation. The water stored is only considered for the water storage tanks and the water bodies. For the energy module, the model makes an hourly energy balance between the energy 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. Each module has two types of input: hourly meteorological data, and hourly demand. The water module requires the precipitation and evaporation hourly data, and the hourly water demand for the inhabitants and irrigation. The energy module needs as input hourly data for the wind speed and/or solar irradiance, and the hourly electricity demand from the urban water cycle. The last is produced by the water module (see Figure 4).

3.3. Multi-objective optimization

We optimize the twelve alternatives using a Pareto-based multi-objective optimization. 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, minimum amount of treated water that is not reused, and renewable electricity shortage. In this process, we use, as input for the model, 36 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:

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

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 (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)

3.4. Evaluation with multi-criteria decision analysis

The twelve optimized alternatives are evaluated using multi-criteria decision analysis. We use the additive multi-attribute value function to determine the (total) value of each alternative as a weighted sum of (individual) values per attribute (Eisenführ et al., 2010). The additive model determines the value $v(a)$ of an alternative a as

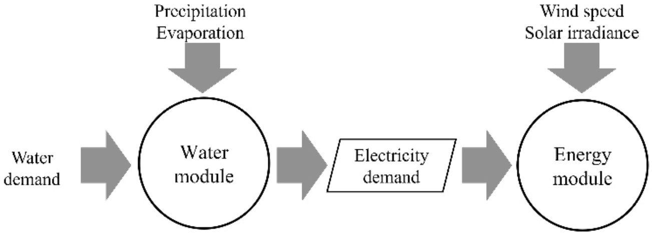


Figure 4. Scheme showing the input for the water and energy modules.

$$v(a) = \sum_{r=1}^{m} w_r v_r(a_r) \tag{2}$$

where $w_r > 0$ and

$$\sum_{r=1}^{m} w_r = 1 \tag{3}$$

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. In Table 1 we define three types of indicators which are performance, economic, and environmental. In addition, we determine their weights (*w)* giving more preference to environmental aspects such as RES penetration and treated water that is not reused, and less preference to economical aspects. The values a_r for each attribute or indicator 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) accumulated precipitation from the data set to see how each alternative performs under those conditions.

Table 1. Indicators for performance, economic, and environmental aspects.

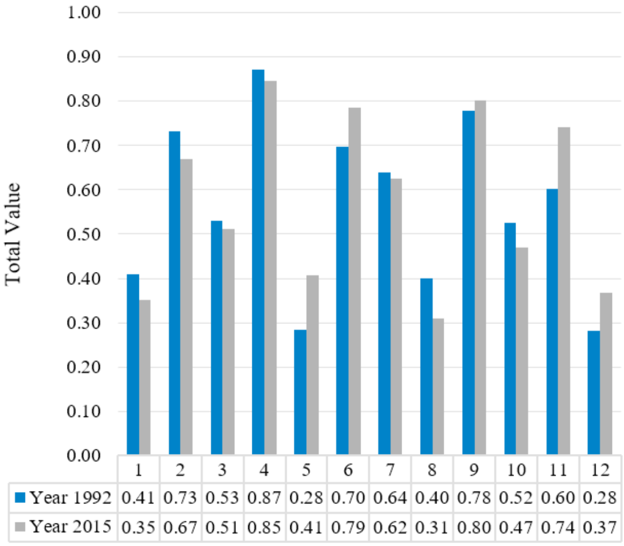
PERFORMANCE	**WEIGHTS**
For Water:	
Water shortage (m^3/month)	0.082
Percentage of time with water shortage (%)	0.091
Percentage of time with the water level from the water bodies below the minimum level (%)	0.018
Water treated but not reused (m^3/month)	0.100
For Energy:	
Renewable Energy production (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 (EUR)	0.069
O&M per year as a percentage of the capital cost (%)	0.064
ENVIRONMENTAL	
CO_2 emissions (10^3 kg CO_2-eq /year)	0.127

4. RESULTS AND DISCUSSION

Figure 5 shows the results from the multi-attribute value function. Each alternative is evaluated under two different scenarios. The scenarios correspond to the years 1992 and 2015. In Figure 5 it is observed that the dominated 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 water that is treated but not reused. This is because they do not consider the reuse of wastewater. . In addition, the alternatives A5 and A4 have lower scores for CO_2-eq emissions. This is because the greenhouse gasses (GHG) Life Cycle emissions for PV panels (91.1 g CO_2-eq kW/h) are higher than those emitted by wind turbine technologies (13 ± 5.2 g $CO_{2,eq}$ kW/h) (Amponsah et al., 2014).

The dominant 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 scenarios. 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 of all the alternatives that consider the reuse of wastewater. Then, it is observed that the best alternative is the one that includes the reuse of wastewater in its design and the use of multiple renewable energy sources.

For this research, we give more importance (higher weights) to the indicators that are related to water and energy security



	1	2	3	4	5	6	7	8	9	10	11	12
■ Year 1992	0.41	0.73	0.53	0.87	0.28	0.70	0.64	0.40	0.78	0.52	0.60	0.28
■ Year 2015	0.35	0.67	0.51	0.85	0.41	0.79	0.62	0.31	0.80	0.47	0.74	0.37

Figure 5. Values obtained from the MCDA for each alternative.

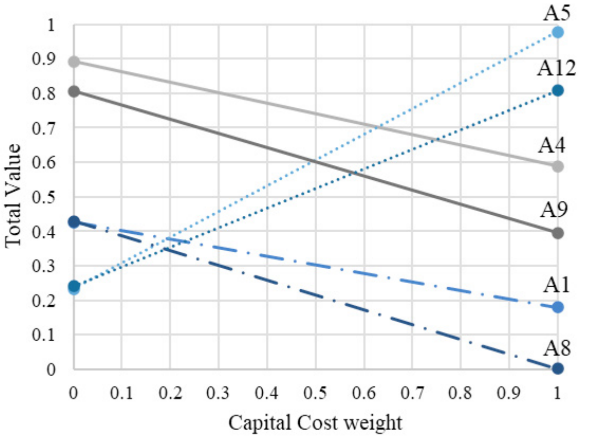


Figure 6. Sensitivity analysis for the weight of the attribute "Capital cost".

and environmental aspects. However, this is not always true for decision-makers. Sometimes economical aspects play a more important role in the rational decision-making process. Figure 6 shows what would be the result of increasing the attribute weight given to the capital cost for the dominated (A1, A5, A8, and A12) and dominant (A4 and A9) alternatives in the scenario with the highest yearly accumulated precipitation. It is observed that the most dominated alternatives A5 and A12 become more attractive as the weight of the capital cost increases. Contrary to that, the dominant alternatives A4 and A9 become less attractive when the decision-maker gives more importance to the capital cost.

5. CONCLUSIONS AND RECOMMENDATIONS

The aim of this paper is to explore to what extent an island can become sustainable in terms of water and energy 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. 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 alternative is determined with the additive multi-attribute value function. In the case study, 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 the capital cost of each alternative the alternatives A5 and A12 could become more attractive than alternatives A4 and A9. This research only considers the interaction between the renewable energy production system and the urban water cycle. Further improvements must be done to integrate the entire electricity consumption from the island and to include the water demand for the HVAC systems. It was shown that giving more importance to the capital cost in the MCDA can make best and worst alternatives exchange places. It is recommended to include the economical aspects of each alternative in the optimization process and to use more than three values per element (x1, x2, …, x8). This would provide a more detailed shape of the Pareto front.

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