Managing Water and Energy on Small Touristic Islands

Study case Caye Chapel

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Supplementary Material

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On the cover

The cover image shows the picture of an island. The image was retrieved from https://www.cayechapel.com (accessed November 02, 2021).

Managing Water and Energy on Small Touristic Islands

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By

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E_{pump}	Pumping station's hourly energy consumption
E_{solar}	Electricity produced by the PV panels
E_{wind}	Electricity produced by the wind turbine
H_d	Discharge head
H_f	Friction losses
H_{op}	Operational head
H_{pump}	Pump's head
H_s	Suction head
H_{solar}	Solar irradiance
P_{factor}	PV panels' performance factor
P_{wind}	Wind turbine's rated power
T_{factor}	PV panels' transposition factor
$a_{r,max}$	Maximum value of the attribute X among the different alternatives
$a_{r,min}$	Minimum value of the attribute X among the different alternatives
a_r	Value of the attribute X for alternative r
t_i	Number of points per attribute (indicator)
v_{10}	Wind speed at 10 meters above mean sea level
$v_r(a_r)$	Valure of the attribute (indicator) value fuction a_r
v_z	Wind speed at the hub's height
w_r	Attribute's (indicator's) weight
x_1	Drinking water storage tank capacity
x_2	Treated wastewater tank capacity
x_3	Rainwater buffer tank capacity
x_4	Treated rainwater storage tank capacity
x_5	Irrigation and water bodies' recovery tank capacity
x_6	Wastewater treatment plant capacity
x_7	Rainwater treatment plant capacity
x_8	Drinking water treatment plant capacity
y_1	Mean water demand shortage
y_2	Mean treated water that is not reused
y_3	Mean renewable electricity shortage
A	PV panels' area
H	Total head
Q	Hourly flow rate
V	Water tank storage volume
X	Attribute or indicator
Y	PV panels' yield
g	Gravity acceleration
$v(a)$	Total value of an alternative a
z	Elevation over mean sea level
μ	Efficiency of the pumping station

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 [1–3]. 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 more electricity would be needed for air conditioning, and at the same time there would be a high risk that the energy industries should have to reduce their production due to a lack of cooling water [2]. 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 [3].

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 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. In this research, "sustainability" is represented by twelve indicators (see Table 39) that are used to measure the performance of the water-energy system, their economic, and the environmental aspects and also to evaluate how sustainable is the water-energy system. 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 RES on an island. The first is the intermittent nature of RES like wind and solar. It produces variances in the power generation [5] that result in hourly electricity outputs that can be between 0 and the maximum power installed [6]. A consequence of this intermittency is that the higher penetration of RES becomes limited [7]. 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 [7], [8]. The mismatch imposes difficulties in matching energy supply with demands [3]. 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 [3]. 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.

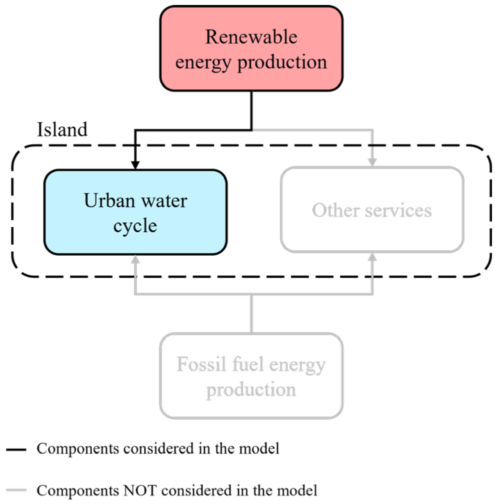

Figure 1. Boundaries of the water-energy system.

1.1 Literature review

This section shows an overview of the literature reviewed related to water, energy, and sustainability in islands. Firstly, it is described the literature related to sustainable energy systems applied to islands and the most relevant findings. Secondly, the papers related to water-energy interactions in small islands and their main conclusions. Lastly, the most popular methods and tools that can be found in literature and that are used to simulate the energy systems.

In the existing literature, some papers study the implementation of renewable energy systems 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. They focus on the energy demands of the entire island. For electricity production, some of them study the use of wind turbines [9–13], and some others the use of solar panels [11], [14]. Due to the intermittent nature of renewable energy sources (RES), it is necessary to implement energy storage technologies to increase the penetration of clean energies [13]. Some papers discuss the implementation of hydrogen technologies [10], [12], [13], [15], [16] and hydro pumped storage [9]. The most relevant findings from these papers are that hydrogen technologies are technologically feasible for stand-alone systems, however, they are too expensive [15]. It was proved for the Island of Mljet (Croatia) that it could become a 100% renewable island concerning electricity [16].

Other papers study the interaction between renewable energy and water systems. They focus mainly on water and energy generation. These papers pay attention to the water-energy nexus by proposing alternatives that allow islands to produce freshwater by using electricity that comes from RES [17–22]. It is considered on their analysis centralized systems for freshwater production and mainly desalination technologies. An exception is Melian et al. [21], who explored driving the entire water cycle (not just the freshwater production) from the island El Hierro (Canary Islands, Spain) solely with the wind energy surplus. Among their scenarios, Melian et al. [21] compare the RES penetration with a centralized and decentralized water production system, while other papers only consider centralized systems. Some of the most relevant conclusions from the papers are that stand-alone hybrid desalination systems are capable to satisfy the water demand for some Greek Islands [17]. The implementation of RES to power the freshwater treatment facilities reduces the water production costs for islands where the current water cost is too high [17], [18]. 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 [21].

1.2 Modeling tools

The energy systems for islands are regularly modeled by using special software like HOMER, H2RES, TRNYSYS16, GTMax, HYDROGEMS, or SimRen [23]. Nevertheless, most of these tools are commercial, except for H2RES which was developed by the Instituto Superior Técnico and the University of Zaberg. H2RES is a balancing tool that simulates the integration of renewable energy into island energy systems [24]. It balances the water and energy demand, supply, and storage, and according to G. Krajačić, N. Duić, and M. da G. Carvalho [16] the "main purpose of the model is energy planning of islands and isolates regions which operate as stand-alone systems" (p.7016). In addition, there is a methodology called RenewIsland which was developed to assess the technical feasibility of various options for integrated energy and resource planning on islands [8]. RenewIsland is based on four steps [8]: 1) mapping the island's needs, 2) mapping the island's resources, 3) devising scenarios with technologies that can use available resources to cover the needs, and 4) modelling scenarios. The last step could be done with the modelling tools already mentioned.

1.3 Island's best practices

According to the Clean energy for EU islands secretariat [25], the best islands practices to supply electricity on touristic islands are the use of subsea cables connected to the mainland, the use of fossil fuels, and in 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 on 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 inhabitants that increase due to tourism between November and April. The energy system is powered by a fuel power plant and a few solar panels. Tlios (Greece) has 500 residents and up to 2,000 visitors on 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.

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 [26]. 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 [27]. 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 [28]. 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 [28]. 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).

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 (R.O.) 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 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, Gas LP generators produce the electricity supply for the island. The island is not connected to the mainland’s electricity grid.

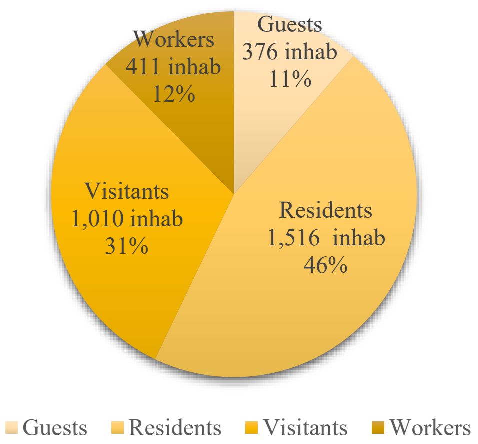

Figure 2. Design population for Caye Chapel.

3 Methodology

This chapter describes the methods and approach followed to determine which alternatives for the water-energy system are the most sustainable for Caye Chapel. This research defines the water-energy system as the renewable electricity system and the urban water cycle of the island. 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 determine which alternative has the higher value and is considered the best alternative.

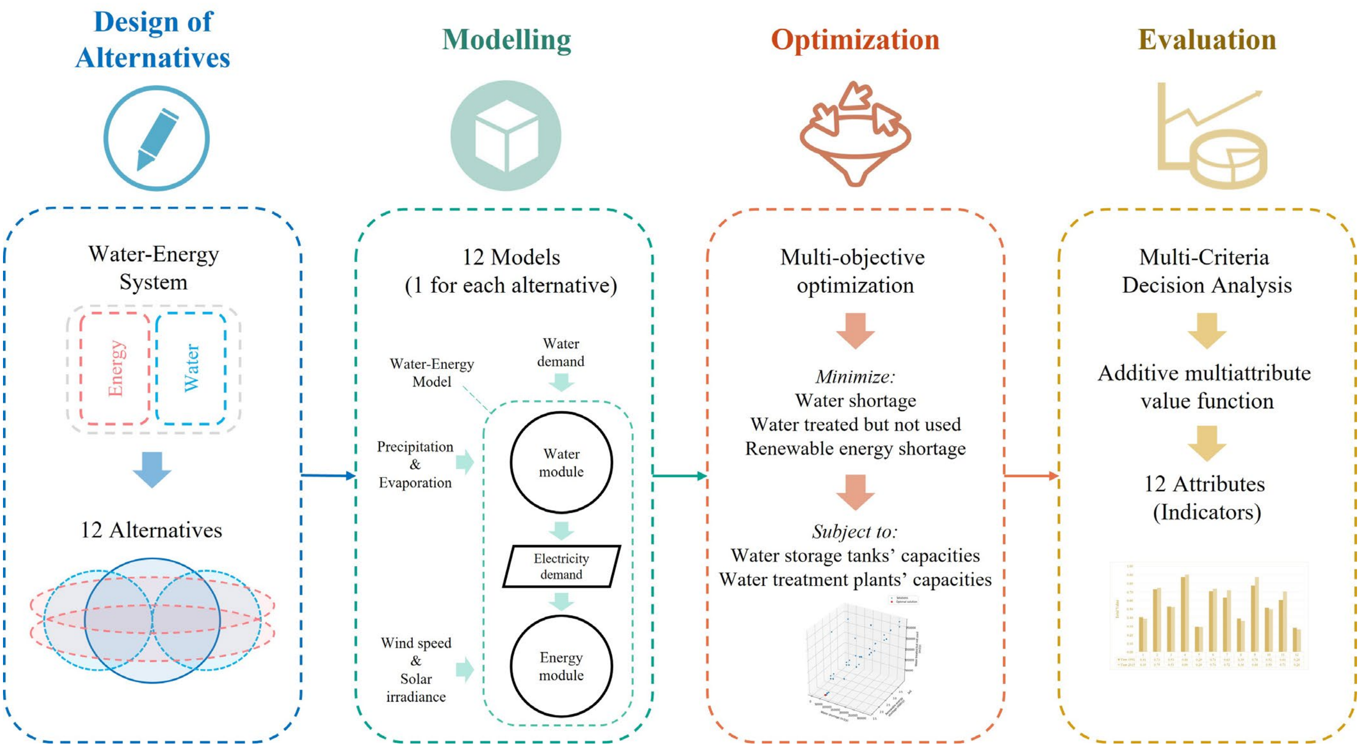

Figure 3. Diagram of the methodology.

4 Design of alternatives

This chapter explains how the alternatives are configured for the water-energy system. Twelve alternatives are designed for the water-energy system. These alternatives are defined by combining different sources, technologies, and operational strategies. 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 technology used for the electricity production. They can use wind turbines, PV panels, or both (see Figure 4). For example, from Figure 4 it is observed that alternative A10 do not reuse the treated wastewater, harvest the rainwater, and the production of renewable electricity comes from wind turbines and PV panels.

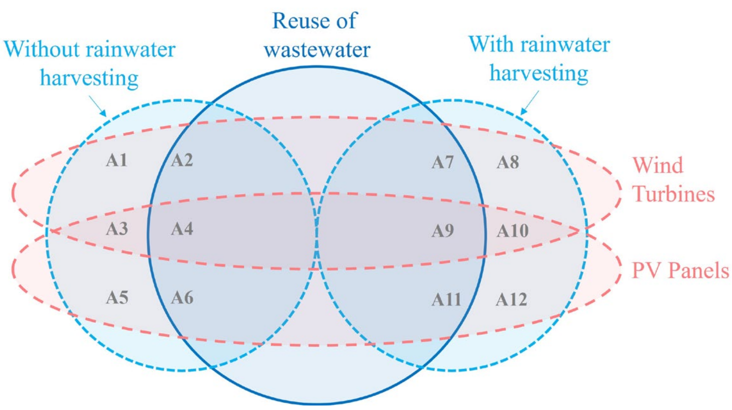

Figure 4. Diagram of the different alternatives for the water-energy system.

In this paper, the alternatives that harvest rainwater treat the rainwater that fall on the golf course's water bodies and use it for irrigation purposes (see Figure 5). The rainwater is not use for potable services because that would lead to higher cost for the investment and operation of the rainwater treatment plant. Furthermore, the rainwater treatment plant will operate intermittently during the year due to the periods where there is no precipitation. The alternatives that consider the reuse of wastewater use the treated wastewater for irrigation and recovery water for the water bodies from the golf course. Those that do not consider the reuse of wastewater still treat the water but then discharge it without further use. Finally, the different alternatives can use for electricity production wind turbines, PV panels, or both.

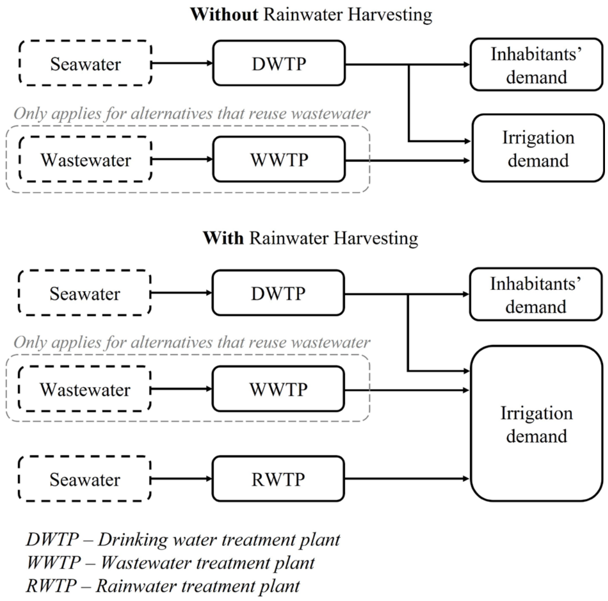

Figure 5. Diagram of alternatives with and without rainwater harvesting.

Each alternative has different elements that interact with each other (see Figure 6). 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, the elements considered are the renewable energy technologies for electricity production and storage. The elements from each alternative are determined using the methodology RenewIsland, which enables assessing 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 needs, 2) mapping the island resources, 3) devising scenarios with technologies that can use available resources to cove the needs, and 4) modelling the scenarios [8].

The water-energy system is divided into the water and energy module, representing the urban water cycle and renewable electricity production, respectively. Taking as an example the alternative A9 (the alternative that considers all the elements from both modules (see Figure 6)), the water module treats seawater in the drinking water treatment plant (DWTP). Then, the drinking water is deposited into the drinking water storage tank (DWT). From the DWT the drinking water can be distributed to the irrigation and recovery storage tank (IWT) with the help of the pumping station no.1 and/or to the potable water services using the pumping station no. 2. The inhabitants use the drinking water that is distributed to the potable water services. The water that is discharged into the sewage system after being used is transported to the wastewater treatment plant (WWTP). The wastewater that goes into the WWTP can be treated or rejected when the wastewater inflow exceeds the WWTP's capacity.

The treated wastewater is pumped into the treated wastewater storage tank (WWT) using pumping station no. 3. The treated wastewater is spilled if the treated wastewater inflow is higher than the available storage capacity of the WWT. The treated wastewater from the WWT is transported to the IWT using pumping station no. 4. The precipitation and evaporation only affect the golf course's water bodies (WB). The water bodies can receive water coming from the IWT. When the water level in the WB is higher than the overflow level, the water can overflow and be transported by gravity to the rainwater buffer tank (RWB) or spilled if the RWB does not have enough available storage capacity. The water inside the RWB is pumped into the rainwater treatment plant (RWTP) using pumping station no. 5. The rainwater is treated and then transported to the treated rainwater storage tank (RWT) using pumping station no. 6. The treated rainwater is spilled if the available storage capacity in the RWT is smaller than the inflow. The water contained in the RWT is transported to the IWT using pumping station no.7. Finally, the IWT can receive water from the DWT, WWT, and/or RWT. The water stored in the IWT is used for irrigation using pumping station no. 8 and/or as recovery water to maintain the water levels in the WB using pumping station no. 9.

The energy module uses wind turbines to produce electricity from wind energy and PV panels to produce electricity from solar energy. 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 enough to satisfy the electricity demand from the urban water cycle, the electricity demand is satisfied with fossil energy sources.

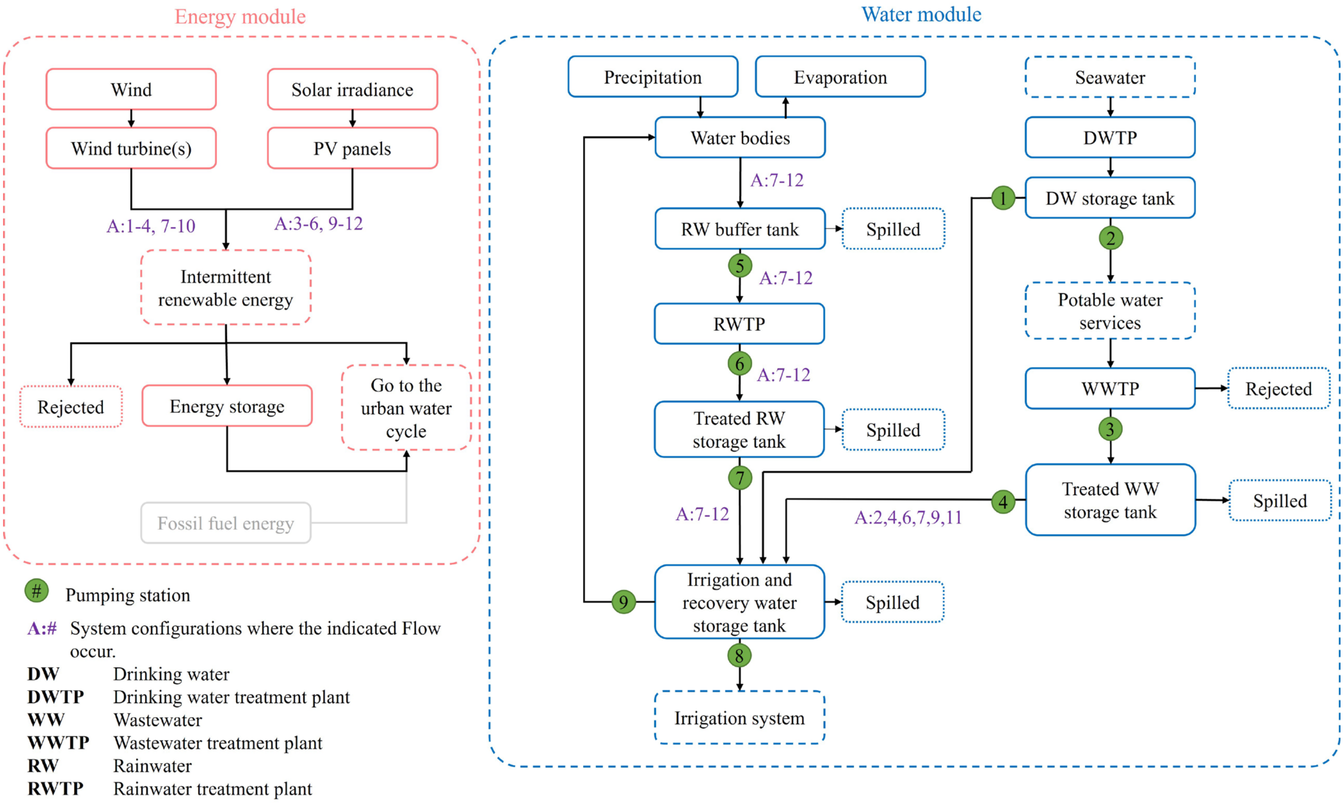

Figure 6. Water-energy system. Elements and their interactions for every alternative.

4.1 RenewIsland methodology

The RenewIsland methodology is a tool that enables the assessment of the technical feasibility of different options for integrated energy and source planning on islands [8]. With this methodology, it is possible to define in a systematic way which technologies and sources for electricity and water production could be feasible for the water-energy system on the island. The methodology is based on a four-step analysis approach that is applied to Caye Chapel:

1. Mapping the island's needs.
2. Mapping the island's resources.
3. Devising scenarios with technologies that can use available resources to cover the needs.
4. Modelling scenarios.

After completing the three first steps, the most feasible options for electricity production are wind and energy conversion systems. For electricity storage, hydrogen technologies are the most feasible. Nevertheless, in this research is also considered the use of batteries. Finally, the methodology suggests that harvesting rainwater and treating seawater are the most viable alternatives for water production. The analysis of the different steps for Caye Chapel are shown below. The methodology provides a questionnaire to guide the designer through each step. The full description of the methodology and steps can be found in the article "RenewIsland methodology for sustainable energy and resource planning for islands" [8].

Step 1: Mapping the needs.

The guide to map the island's needs is shown in Table 1. The needs that are identified for Caye Chapel are described in Table 2. To have a sustainable development, the electricity and water demand are considered as "high level" regardless of the actual demand[8]. It is assumed that the Hotel and Residences will use reusable recipients and products for daily activities. Therefore, the waste treatment is considered to be a medium level. The wastewater treatment is also regarded as "medium level" because the water demand for irrigation is much greater than the inhabitant's demand. All the needs' geographical distribution are "concentrated" since the island has a small extension (114 ha).

Table 1. RenewIsland: Mapping the island/remote area community needs (source:[8])

Needs	Level	Geographic distribution	Code	Level	Distribution
Electricity	Low, medium or high	Dispersed, concentrated	Elect	+ L/M/H/−	+ D/C/−
Heat	Low, medium or high	Dispersed, concentrated	Heat	+ L/M/H/−	+ D/C/−
Cold	Low, medium or high	Dispersed, concentrated	Cold	+ L/M/H/−	+ D/C/−
Transport fuel	Low, medium or high	Short, long distance	Tran	+ L/M/H/−	+ S/L/−
Water	Low, medium or high	Dispersed, concentrated	Water	+ L/M/H/−	+ D/C/−
Waste treatment	Low, medium or high	Dispersed, concentrated	Waste	+ L/M/H/−	+ D/C/−
Wastewater treatment	Low, medium or high	Dispersed, concentrated	WWT	+ L/M/H/−	+ D/C/−

Table 2. Caye Chapel's needs.

Needs	Level	Geographic distribution	Code	Level	Distribution	Full Code
Electricity	High	Concentrated	Elect	H	C	ElectHC
Heat	Low	Concentrated	Heat	L	C	HeatLC
Cold	High	Concentrated	Cold	H	C	ColdHC
Transport fuel	Low	Short	Tran	S	S	TranSS
Water	High	Concentrated	Water	H	C	WaterHC
Waste treatment	Medium	Concentrated	Waste	M	C	WasteMC
Wastewater treatment	Medium	Concentrated	WWT	M	C	WWTMC

Step 2: Mapping the resources.

This step identifies the available resources and their carriers for the island using Table 3 and Table 4. The results of the analysis are shown in Table 5 and Table 6. In Table 5, it is observed that wind and solar energy are considered high-level resources, while hydro, biomass, and geothermal resources with a low level. This is because the island has a flat topography, it is not expected to produce large amounts of waste, and there is not enough information to determine if geothermal energy is an option is this island. For the energy import infrastructure, it is considered that the island is not connected to the mainland. Therefore, there is just an import of oil derivatives. The primary water resources on the island are considered to be precipitation and seawater. There is not enough information to determine if enough groundwater is available on the island. The energy carriers are determined by using the previous analysis. In Table 6, it is shown that the alternatives can be electricity, district cooling, hydrogen, petrol, or LP gas. Nevertheless, for this research, only electricity is considered.

Table 3. RenewIsland: Mapping the island/remote area available resources (source: [8])

Resource	Level	Code			
Local primary energy					
Wind	Low, medium or high	Wind	WindL	WindM	WindH
Solar	Low, medium or high	Solar	SolarL	SolarM	SolarH
Hydro (height)	Low, medium or high	Hydro	HydroL	HydroM	HydroH
Biomass	Low, medium or high	Biom	BiomL	BiomM	BiomH
Geothermal	Low, medium or high	Geoth	GeothL	GeothM	GeothH
Energy import infrastructure					
Grid connection	None, weak, strong	Grid	GridN	GridW	GridS
Natural gas pipeline	No, yes	NGpl	NGplN		NGplY
LNG terminal	No, yes	LNGt	LNGtN		LNGtY
Oil terminal/refinery	No, yes	OilR	OilRN		OilRY
Oil derivatives terminal	No, yes	OilD	OilDN		OilDY
Water					
Precipitation	Low, medium or high	H2OP	H2OPL	H2OPM	H2OPH
Ground water	Low, medium or high	H2OG	H2OGL	H2OGM	H2OGH
Water pipeline	No, yes	Aqua	AquaN		AquaY
Sea water	No, yes	H2OS	H2OSN		H2OSY

Table 4. Potential energy carriers (source: [8])

Potential energy carriers	Condition	Code
Electricity	IF ElectC	ECEl
District heating	IF HeatHC	ECDH
District cooling	IF ColdHC	ECDC
Hydrogen	IF (Tran OR ElectC)	ECH2
Natural gas	IF (NGplY OR LNGtY)	ECNG
Biogas	IF (BiomH OR WasteHC OR WWTHC)	ECBG
Petrol/Diesel	IF (OilRY OR OilDY)	ECPD
Bioethanol	IF (BiomH OR WasteHC)	ECEt
LPG	IF (OilRY OR OilDY)	ECLPG
Biodiesel	IF (BiomH OR WasteHC)	ECBD

Table 5. Caye Chapel's available resources.

Resource	Level	Code	Level	Full Code
Local primary energy				
Wind	High	Wind	H	WindH
Solar	High	Solar	H	SolarH
Hydro (height)	Low	Hydro	L	HydroL
Biomass	Low	Biom	L	BiomL
Geothermal	Low	Geoth	L	GeothL
Energy import infrastructure				
Grid connection	None	Grid	N	GridN
Natural gas pipeline	No	NGpl	N	NGplN
LNG terminal	No	LNGt	N	LNGtN
Oil terminal/refinery	No	OilR	N	OilRN
Oil derivatives terminal	Yes	OilD	Y	OilDY
Water				
Precipitation	High	H2OP	H	H2OPH
Ground water	Low	H2OG	L	H2OGL
Water pipeline	No	AquaN	N	AquaNN

Sea water	Yes	H2OS	Y	H2OSY

Table 6. Caye Chapel's energy carriers.

Potential energy carriers	**Code**
Electricity	ECEI
Distruct cooling	ECDC
Hydrogen	ECH2
Petrol/Diesel	ECPD
LPG	ECLPG

Step 3: Devising scenarios with technologies that can use available resources to cover the needs.

This step has three substeps that help identify the feasibility of water and energy production technologies, storage, and integration of the different flows.

Substep 3.1: Feasibility of technologies.

Table 7 helps identify the potential delivery technologies that can be integrated into the island. The results of this analysis are shown in Table 8. The methodology suggests that the possible electricity conversion technologies should be a Wind Energy Conversion System (WECS) and Solar Energy Conversion System-Thermal (SECS-Thermal). In addition, it suggests other technologies like a diesel engine, combined cycle gas turbine, and fuel cells. For this research, the SECS-Thermal is replaced for solar PV. The reason is that there is more available background information for modelling the PV panels for the energy system. For the water supply, the technologies are water collection and desalination.

Table 7. RenewIsland: Potential delivering technologies (source: [8])

Technology	Condition	Code
Electricity conversion system		
WECS (wind)	IF (ElectM OR ElectH) AND (WindM OR WindH)	WECS
SECS-PV (solar PV)	IF (ElectL OR ElectM) AND (SolarM OR SolarH)	PV
SECS-Thermal (solar thermal electricity)	IF (Elect) AND (SolarH)	SECS
HECS (hydro)	IF (Elect) AND (HydroM OR HydroH)	HECS
GECS (geothermal)	IF (ElectM OR ElectH) AND (GeothH)	GECS
BECS (biomass)	IF (ElectM OR ElectH) AND (BiomH)	BECS
DEGS (Diesel engine)	IF (Elect) AND (NGplY OR LNGtY OR OilRY OR OilDY)	DEGS
CCGT (combined cycle gas turbine)	IF (ElectH) AND (NGplY OR LNGtY OR OilRY OR OilDY)	CCGT
FC (fuel cell)	IF (Elect) AND (H2Fuel)	FC
Heating system		
Solar collectors	IF (Heat) AND (SolarM OR SolarH)	STCo
Geothermal	IF (HeatH) AND (GeothM OR GeothH)	GeTH
Heat pumps	IF (HeatH AND ECEl)	HPHe
Biomass boilers	IF (HeatH) AND (BiomM OR BiomH)	BMBo
Gas boilers	IF (Heat) AND (NGplY OR LNGtY OR OilRY OR OilDY OR WasteG OR WWG)	GSBo

Cooling		
Solar absorbers	IF (Cold) AND (SolarH)	SAbs
Heat pumps	IF (ColdH AND ECEl)	HPCo
Gas coolers	IF (ColdH) AND (NGplY OR LNGtY OR OilRY OR OilDY OR WasG OR WWtG)	GSCo
Electricity coolers	IF (ColdH AND ECEl)	ELCo
Fuel		
Hydrogen	IF (Tran) AND (ECH2)	H2Fuel
Electricity	IF (Tran) AND (ECEl)	ElFuel
Bioethanol	IF (Tran) AND (ECEt)	EthanolFuel
Biodiesel	IF (Tran) AND (ECBD)	BDFuel
LPG	IF (Tran) AND (ECLPG)	LPGFuel
Natural Gas	IF (Tran) AND (ECNG)	NGFuel
Biogas	IF (Tran) AND (ECBG)	BGFuel
Petrol/Diesel	IF (Tran) AND (ECPD)	PDFuel
Water supply		
Water collection	IF (Water) AND (H2OPM OR H2OPH)	WaterC
Water wells	IF (Water) AND (H2OGM OR H2OGH)	WaterW
Desalination	IF (Water) AND (H2OSY)	WaterD
Waste		
Incineration	IF (WasteHC)	WasteI
Gasification	IF (WasteHC)	WasteG
Wastewater treatment		
Gasification	IF (WWTHC)	WWG

Table 8. Caye Chapel's potential delivery technologies.

Technology	Code
Electricity conversion system	
WECS (wind)	WECS
SECS-Thermal (solar thermal electricity)	SECS
DEGS (Diesel engine)	DEGS
CCGT (combined cycle gas turbine)	CCGT
FC (fuel cell)	FC
Water supply	
Water collection	WaterC
Desalination	WaterD

Substep 3.2: Feasibility of storage.

It is usually necessary to have enough water and energy storage facilities when there is no connection to the mainland grid. Table 9 is a guide to determining the feasibility of the storage technologies. The results of the analysis are shown in Table 10. It is observed that the methodology considers feasible the storage of electricity using hydrogen technologies. The method discards batteries because hydrogen can be a potential energy carrier. Nevertheless, for this research, the use of batteries is considered.

Table 9. RenewIsland: Potential storage technologies (source: [8]).

Electricity storage system		
Reversible hydro	IF (WECS AND HECS)	RHECS
Electrolyser + hydrogen	IF (WECS OR SECS OR PV) AND NOT HECS	ELYH2
Reformer + hydrogen	IF (ECNG OR ECBG OR ECPD OR ECEt OR ECLPG OR ECBD) AND NOT HECS	REFH2
Batteries	IF (SECS OR PV) AND NOT HECS AND NOT ECH2	BAT
Heat storage		
Heat storage	IF (HeatH)	HeatS
Cold bank	IF (ColdH)	ColdS
Fuel		
Hydrogen	IF H2Fuel	H2stor
Bioethanol	IF EthanolFuel	Ethanolstor
Biodiesel	IF BDFuel	BDstor
LPG	IF LPGFuel	LPGstor
NG	IF NGFuel	NGstor
BG	IF BGFuel	BGstor
Petrol/Diesel	IF PDFuel	PDstor
Water, waste and wastewater		
Water	IF Water	WaterS
Waste fill	IF Waste	WasteF
Wastewater tanks	IF WWT	WWstor

Table 10. Caye Chapel's potential storage technologies.

Technology	**Code**
Electricity storage system	
Electrolyser + hydrogen	ELYH2
Reformer + hydrogen	REFH2
Batteries	*According to the methodology it is not possible because we have hydrogen as energy carrier.*
Heat storage	
Cold bank	ColdS
Fuel	
Hydrogen	H2stor
LPG	LPGstor
Petrol/Diesel	PDstor
Water, waste and wastewater	
Water	WaterS
Wastewater tanks	WWstor

Substep 3.3: Integration of flows.

Some resources and commodities flows can be integrated to increase the system's efficiency. Table 11 provides a guide for the possible integration of the different flows. The results of this analysis (see Table 12) show that a possible integration of technologies can be done by using combined power and hydrogen production. Also, combined heat, power, cold, and hydrogen production is an option. However, the last option is discarded because this research is only focused on electricity production.

Table 11. RenewIsland: Integrating the flows (source: [8]).

Integration technology	Condition	Code
Combined heat and power	IF (Elect PROPORTIONAL Heat) AND (DEGS OR CCGT OR FC OR BECS OR SECS OR GECS)	CHP
Combined heat and cold	IF (Heat PROPORTIONAL Cold)	CHC
Trigeneration	IF (Elect PROPORTIONAL (Heat + Cold)) AND (DEGS OR CCGT OR FC OR BECS OR SECS OR GECS)	3G-HPC
Combined water and power	IF (HydroM OR HydroH) AND Water	CWP
Combined waste treatment and heat generation	IF (WasteI AND (HeatM OR HeatH))	CWTH
Combined waste treatment and power generation	IF (WasteI AND (ElectM OR ElectH))	CWTP
Combined waste treatment and heat and power generation	IF (WasteI AND (ElectM OR ElectH) AND Elect PROPORTIONAL Heat)	3G-WTHP
Combined waste treatment and heat, power and cold generation	IF (WasteI AND (ElectM OR ElectH) AND Elect PROPORTIONAL (Heat + Cold))	4G-WTHPC
Combined waste treatment and bioethanol production	IF (WasteG AND ECEt)	CWTC2H5OH
Combined waste treatment and gas production	IF (WasteG AND ECBG)	CWTGas
Combined wastewater treatment and gas production	IF (WWG AND ECBG)	CWWTGas
Combined power and hydrogen production	IF (WECS OR PV) AND ECH2	CPH2
Combined heat, power and hydrogen production	IF (SECS OR BECS OR GECS) AND ECH2	3G-HPH2
Combined heat, power, cold and hydrogen production	IF (SECS OR BECS OR GECS) AND ECH2	4G-HPCH2

Table 12. Technologies that could be integrated in Caye Chapel's system.

Integration technology	Code
Combined power and hydrogen production	CPH2
Combined heat, power and hydrogen production	3G-HPH2
Combined heat, power, cold and hydrogen production	4G-HPCH2

Step 4: Modelling.

The modelling process is developed in Python. The model is described in more detail in chapter 5 .

4.2 Alternative 1

Alternative A1 do not consider rainwater harvesting, does not reuse wastewater and uses wind turbines to produce electricity.

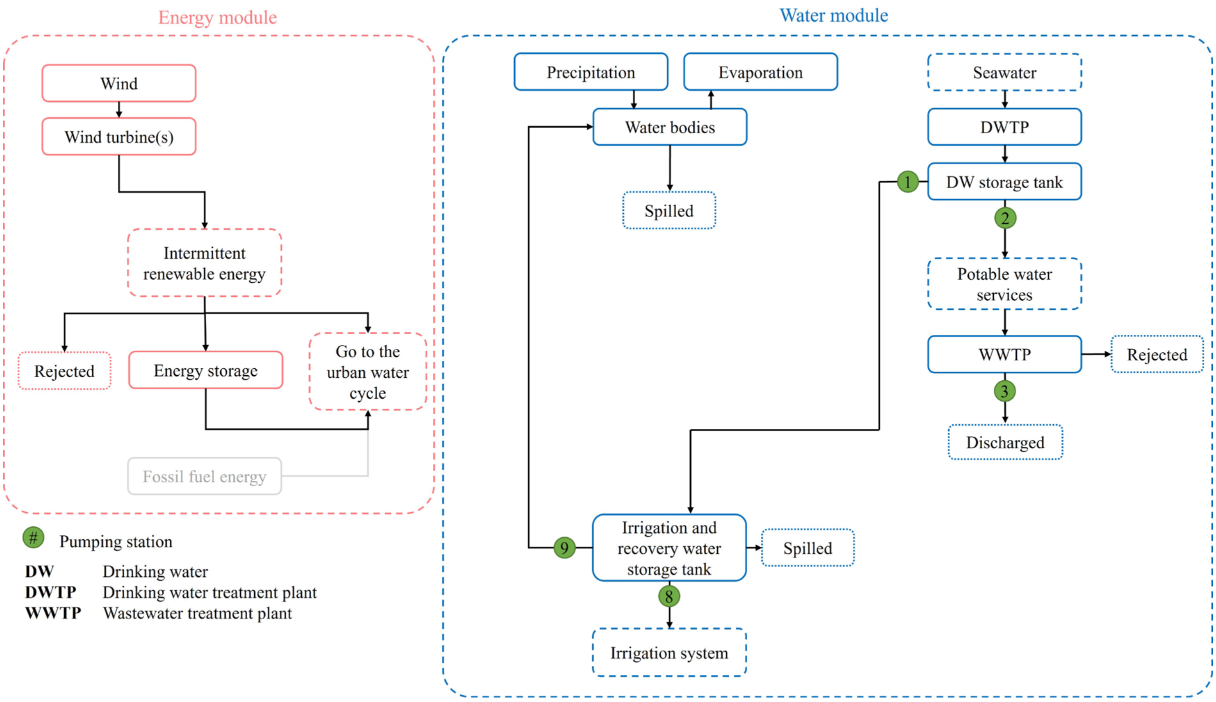

Figure 7. Alternative 1 water-energy system: elements and their interactions.

4.3 Alternative 2

Alternative A2 do not consider rainwater harvesting, reuses wastewater, and uses wind turbines to produce electricity.

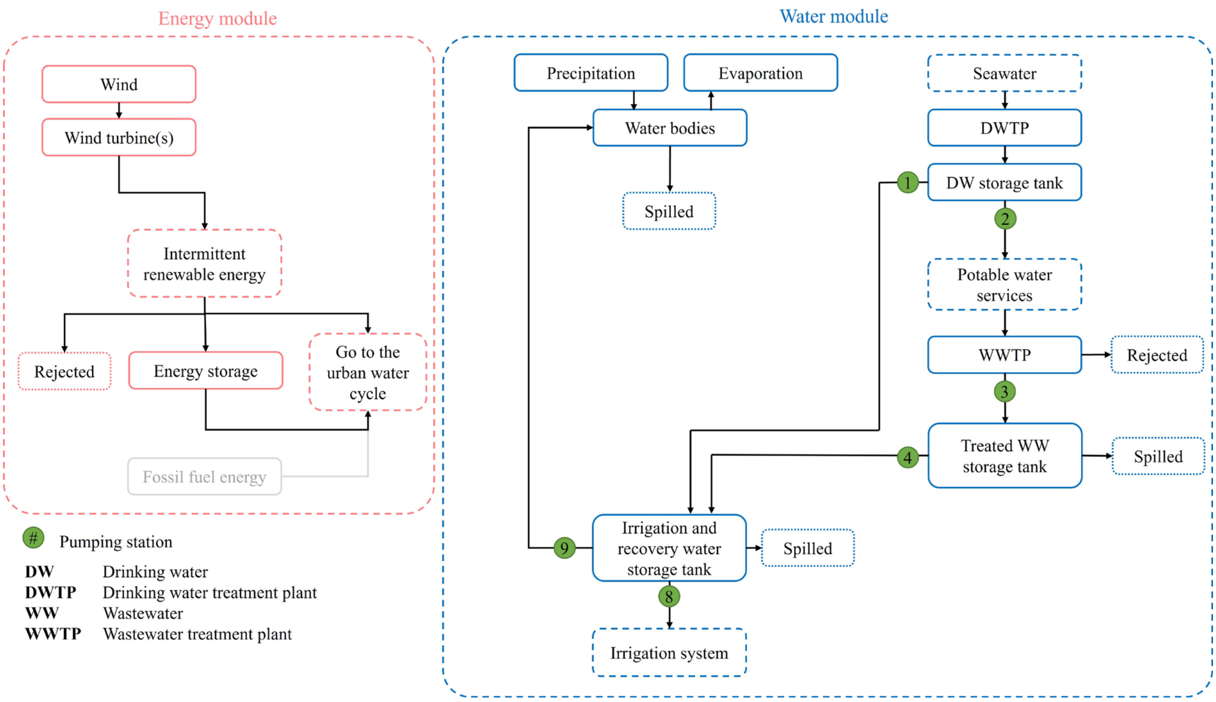

Figure 8. Alternative 2 water-energy system: elements and their interactions.

4.4 Alternative 3

Alternative A3 do not consider rainwater harvesting, does not reuse wastewater, and uses wind turbines and PV panels to produce electricity.

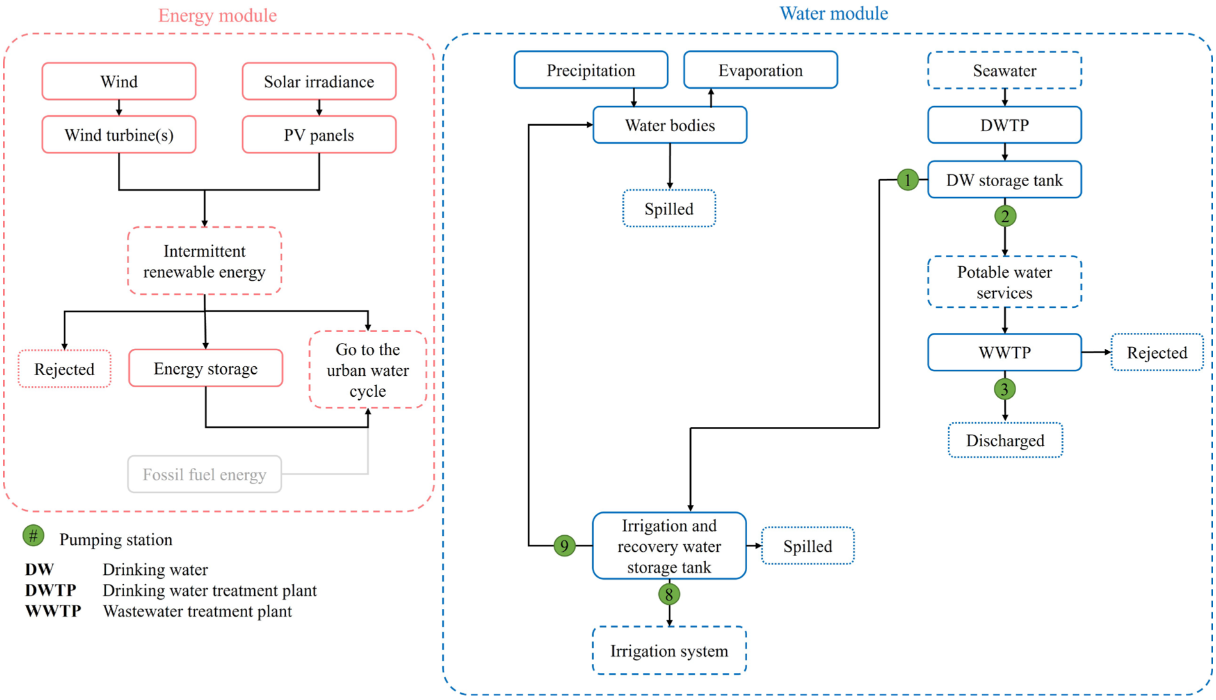

Figure 9. Alternative 3 water-energy system: elements and their interactions.

4.5 Alternative 4

Alternative A4 do not consider rainwater harvesting, reuses wastewater, and uses wind turbines and PV panels to produce electricity.

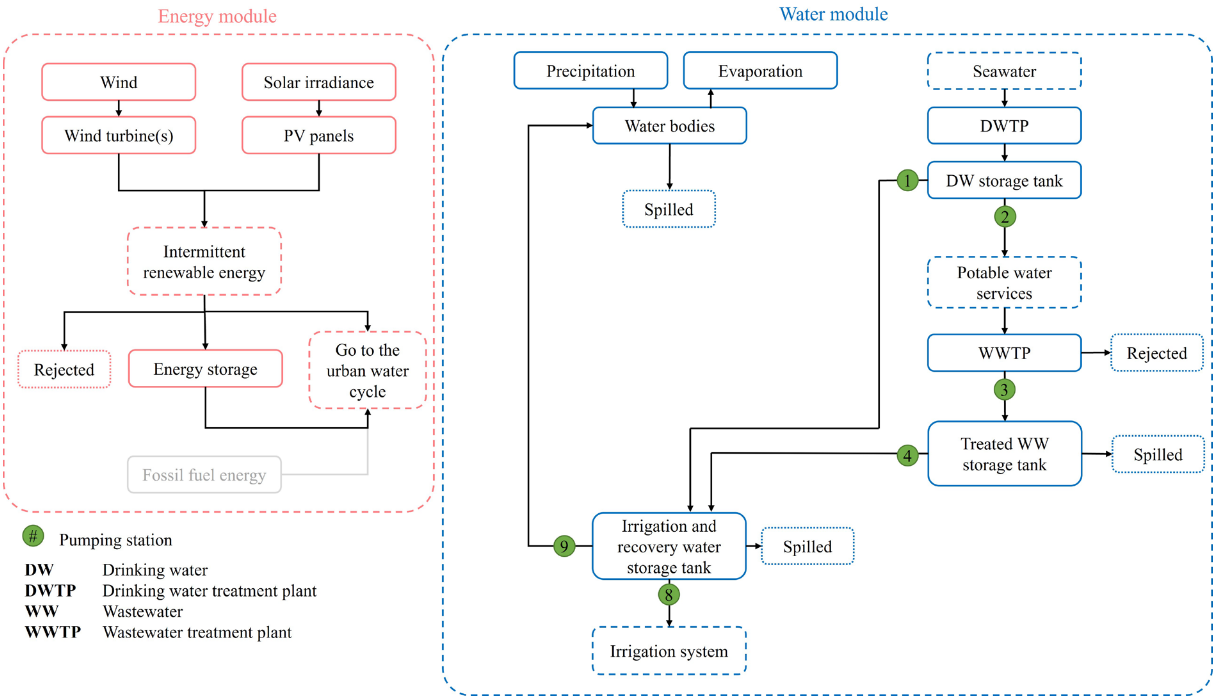

Figure 10. Alternative 4 water-energy system: elements and their interactions.

4.6 Alternative 5

Alternative A5 do not consider rainwater harvesting, does not reuse wastewater, and uses PV panels to produce electricity.

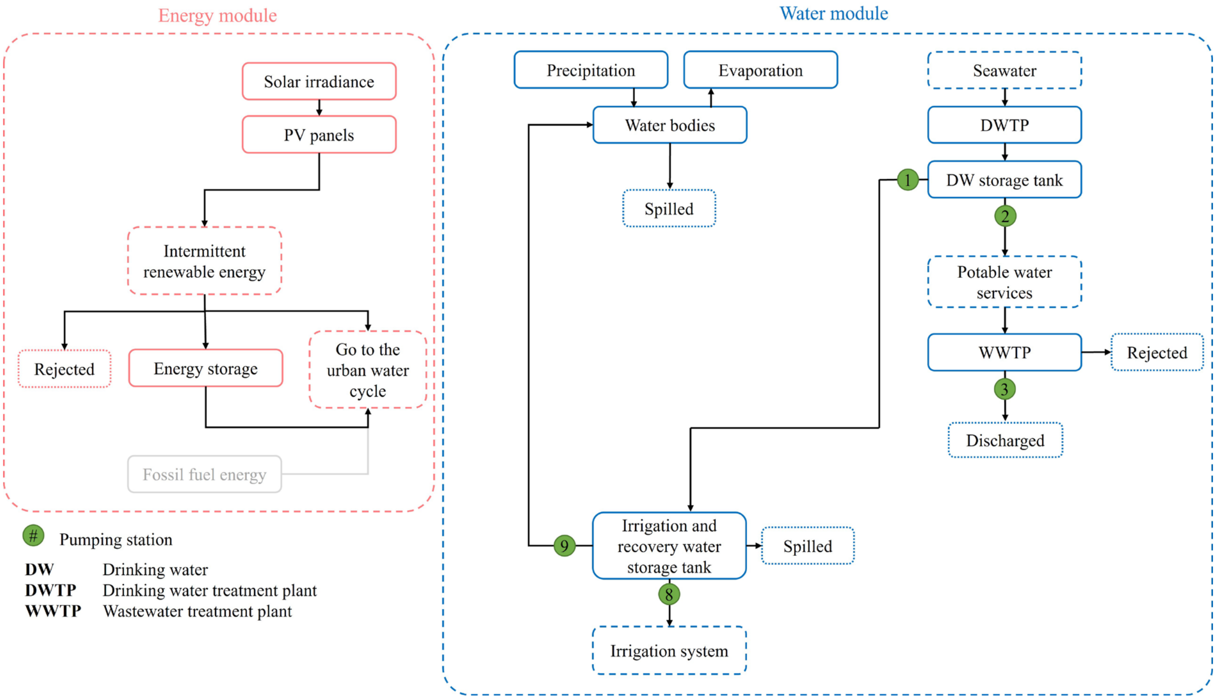

Figure 11. Alternative 5 water-energy system: elements and their interactions.

4.7 Alternative 6

Alternative A6 do not consider rainwater harvesting, reuses wastewater, and uses PV panels to produce electricity.

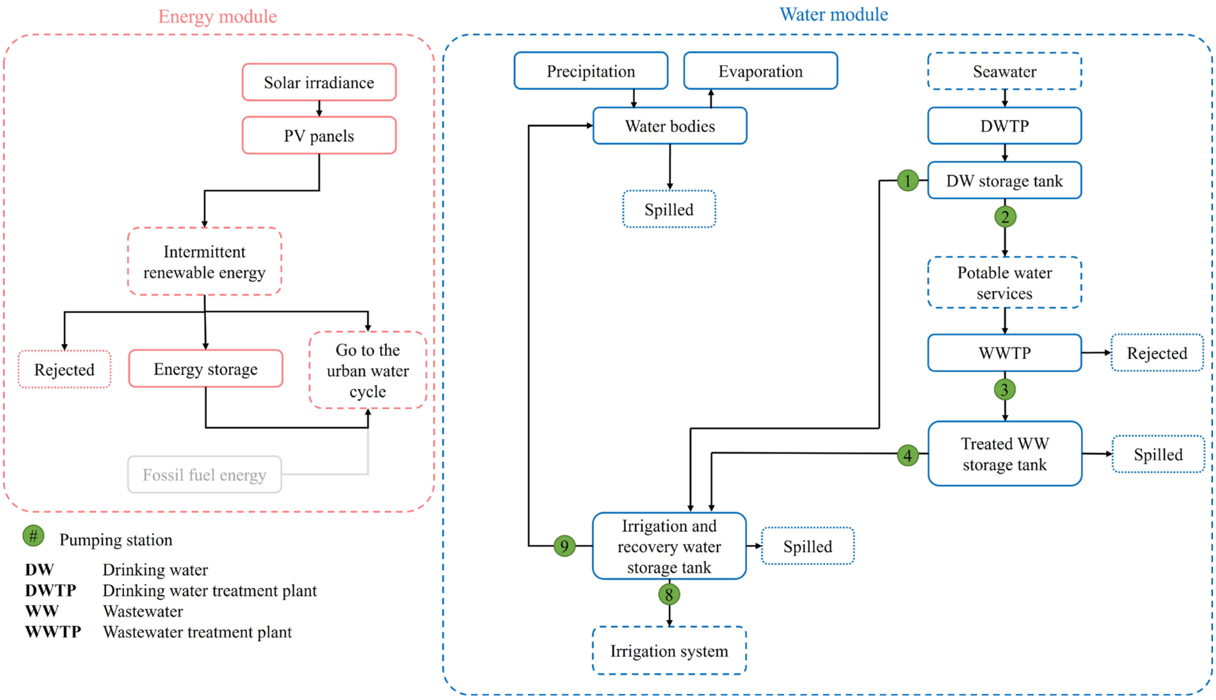

Figure 12. Alternative 6 water-energy system: elements and their interactions.

4.8 Alternative 7

Alternative A7 considers rainwater harvesting, reuses wastewater, and uses wind turbines to produce electricity.

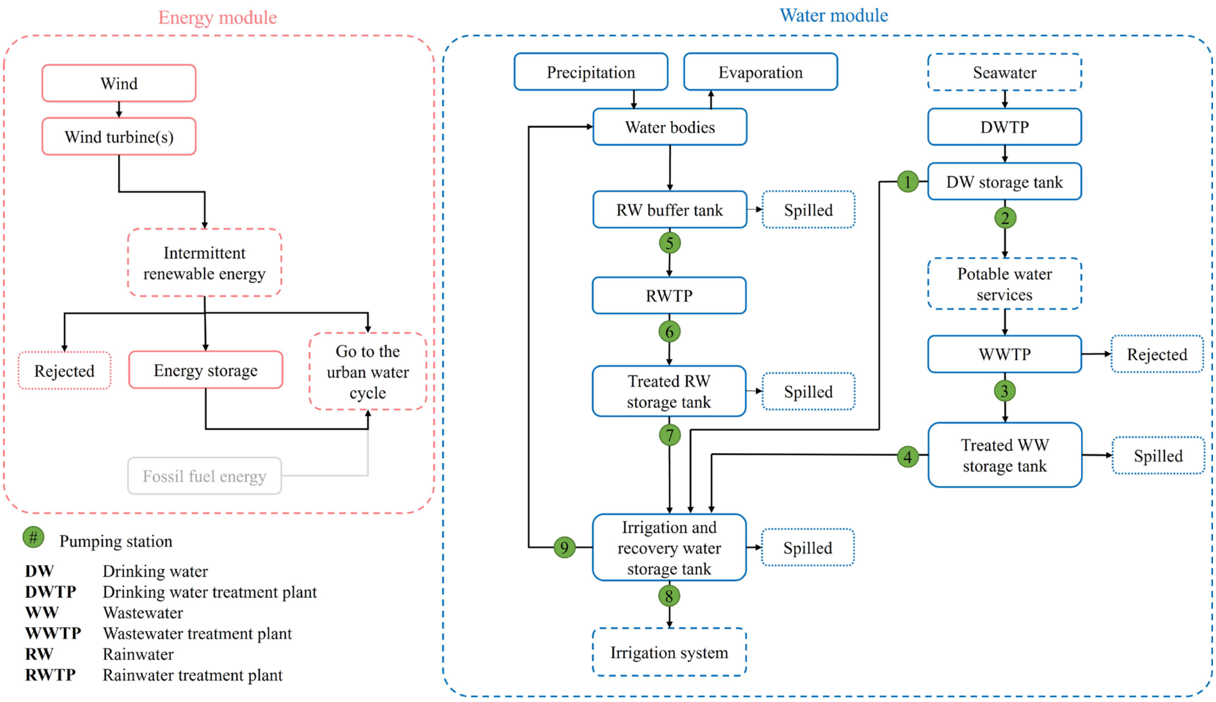

Figure 13. Alternative 7 water-energy system: elements and their interactions.

4.9 Alternative 8

Alternative A8 considers rainwater harvesting, does not reuse wastewater and uses wind turbines to produce electricity.

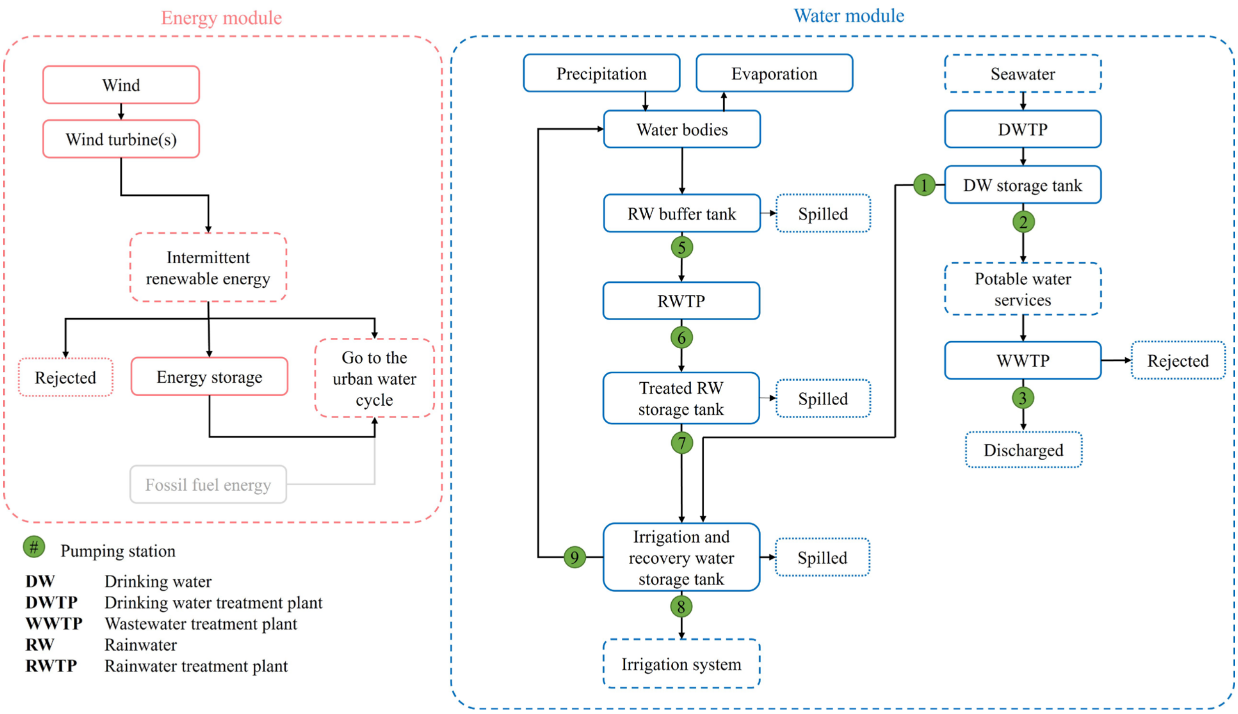

Figure 14. Alternative 8 water-energy system: elements and their interactions.

4.10 Alternative 9

Alternative A9 considers rainwater harvesting, reuses wastewater, and uses wind turbines and PV panels to produce electricity.

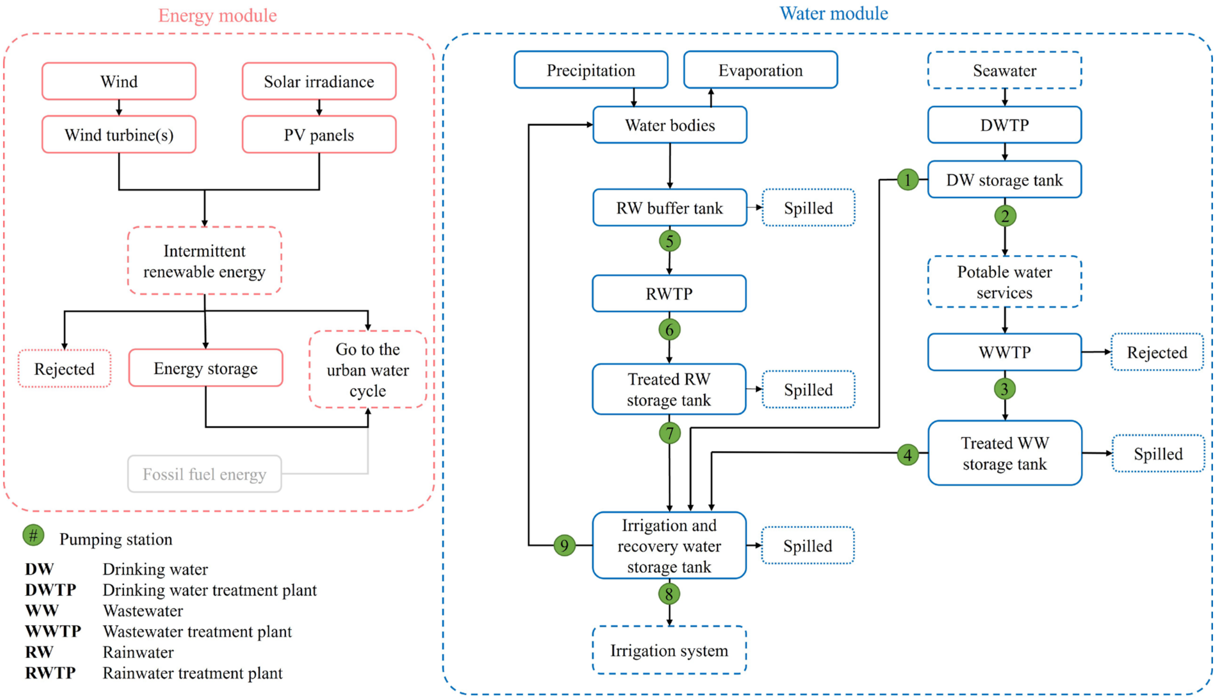

Figure 15. Alternative 9 water-energy system: elements and their interactions.

4.11 Alternative 10

Alternative A10 considers rainwater harvesting, does not reuse wastewater, and uses wind turbines and PV panels to produce electricity.

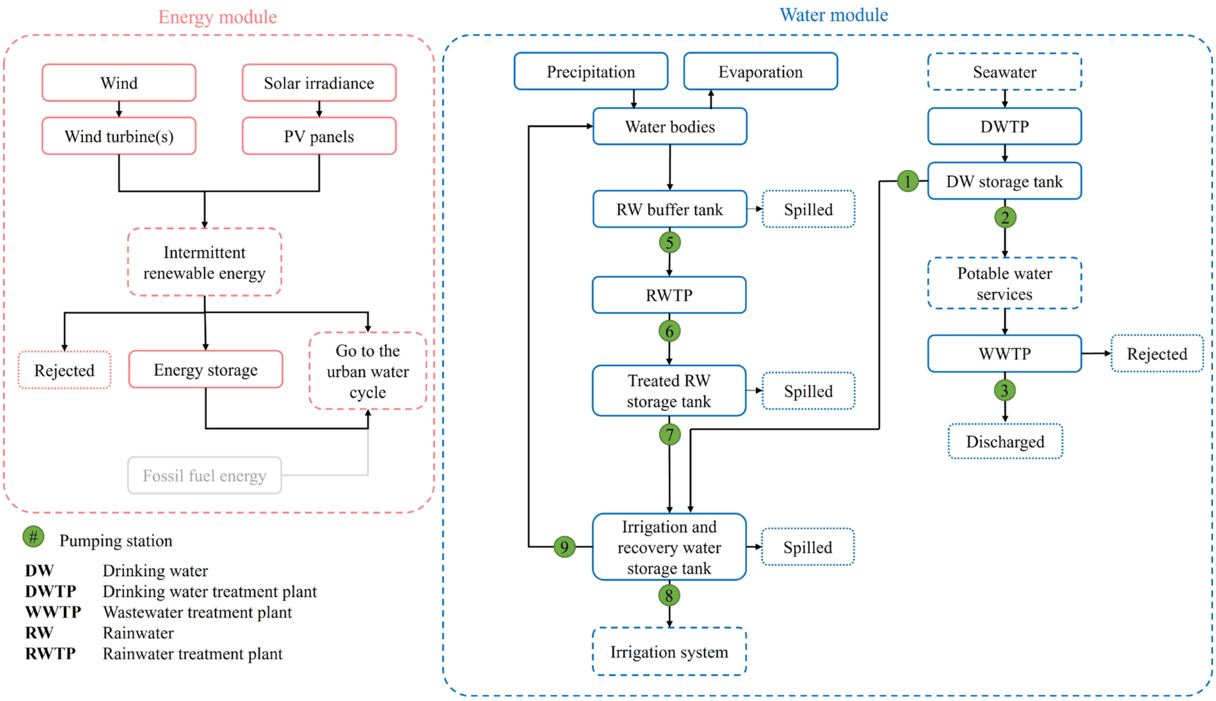

Figure 16. Alternative 10 water-energy system: elements and their interactions.

4.12 Alternative 11

Alternative A11 considers rainwater harvesting, reuses wastewater, and uses PV panels to produce electricity.

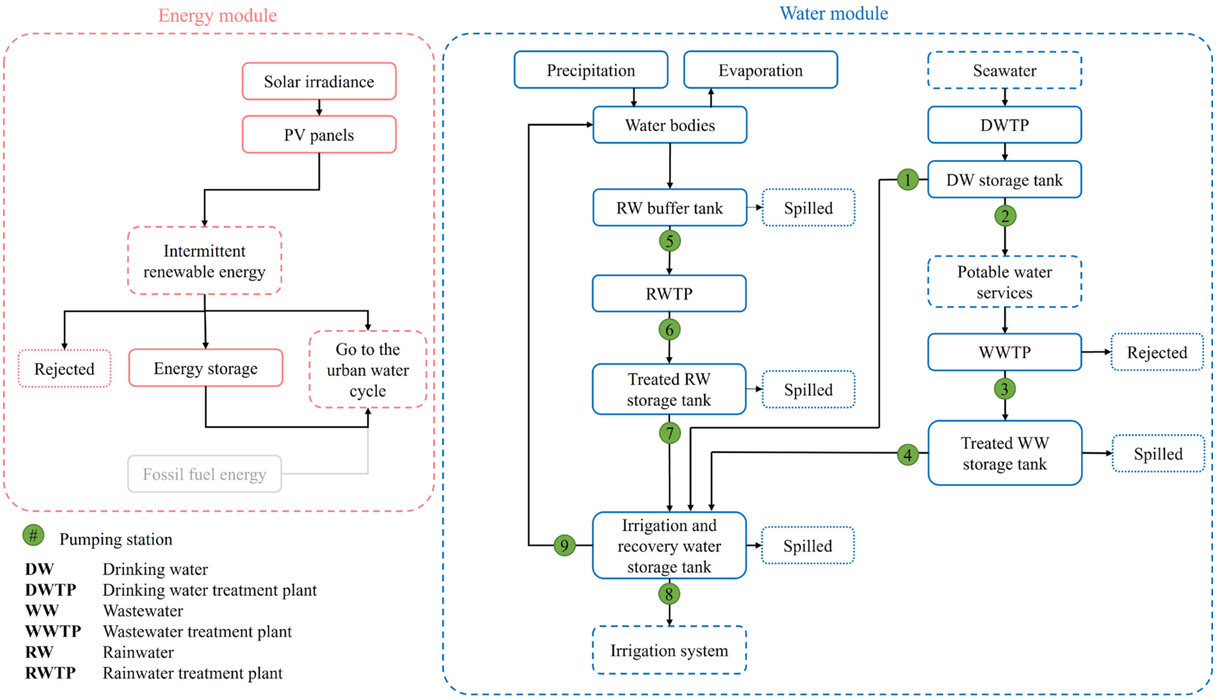

Figure 17. Alternative 11 water-energy system: elements and their interactions.

4.13 Alternative 12

Alternative A12 considers rainwater harvesting, does not reuse wastewater, and uses PV panels to produce electricity.

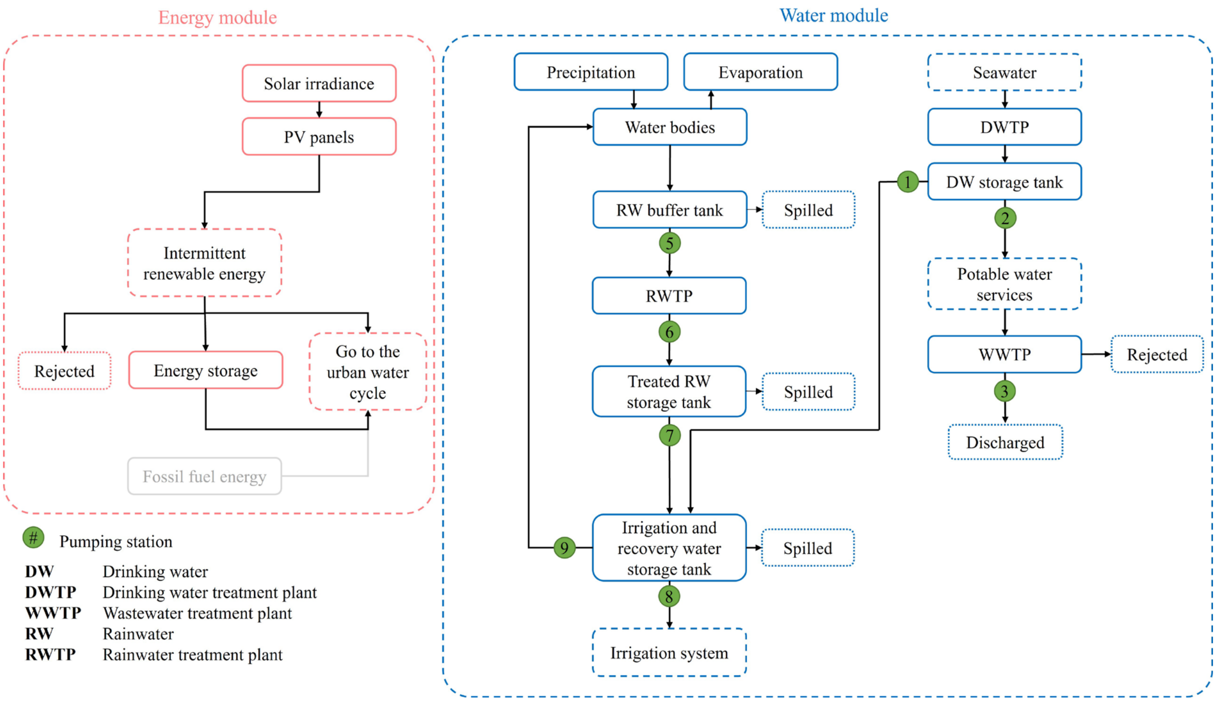

Figure 18. Alternative 12 water-energy system: elements and their interactions.

5 Modelling

This chapter describes the elements that integrate the model for the water-energy system. 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 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 (see Appendix I), which also makes these balances, but in addition, it considers heat and hydrogen balances [29], [30]. The model comprises two modules corresponding to the water and energy systems, respectively. 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 hourly input data for the wind speed and/or solar irradiance and the hourly electricity demand from the urban water cycle. The water module produces the last (see Figure 19).

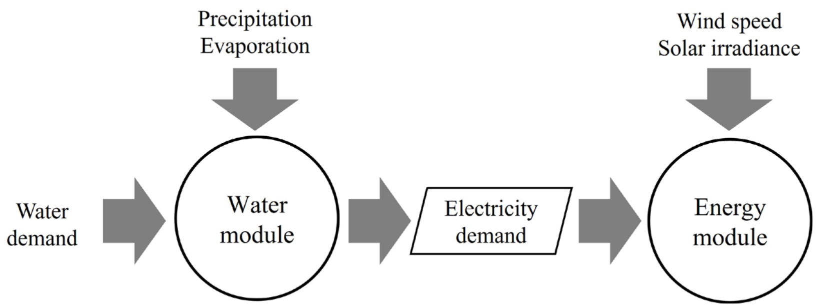

Figure 19. Diagram of the input for the water and energy modules.

5.1 Water module

This section describes the elements from the water module. It explains how the elements are integrated into the model and how they work. The elements inside the water module are the water treatment plants, the water storage tanks, and the pumping stations. The model performs an hourly water balance on each element for the water module between the influent, effluent, water losses, and water stored. The module inputs are the precipitation and evaporation hourly data, the irrigation water demand constant through the year, and the inhabitants' water demand with hourly and monthly variations. The water losses considered in the system are localized in the potable water services since not all the served water becomes wastewater. Water losses occur in the rainwater and wastewater treatment facilities due to evaporation and sludge removal and at the golf courses' water bodies due to evaporation.

For the water storage tanks, the model performs a lecture on the amount of water stored in the different tanks on every hourly 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 goes into each element is restricted by the hourly capacity of the water treatment plants, the pumping capacity of the inlet pumping stations, and the available storage capacity in the water tank. The amount of water that goes out from each storage tank is determined by the inhabitants' and/or irrigation water demand, the capacity of the outlet pumping station, and the available volume of water stored in the tank. For the cases where the inhabitants' and irrigation demand share the same water source, the model gives preference to the inhabitants' water demand. After defining how much water goes in and out of each storage tank, the model makes a 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. The model decides how much water should go inside and outside depending on two water levels: the set and the overflow level. The model will 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 when the water level is higher than the set level but lower than the overflow level. The overflow level determines when does the water bodies start to spill water. Then, at the beginning of every time step, the model makes a water balance between the inflow and outflow from the previous time step and the precipitation and evaporation occurring on the current timestep. After that, it defines the water level and determines how much water should go in and/or out. The water that should go in depends on the water level relative to the set level. However, the amount of water that goes into the water body depends on the pump capacity of the inlet pumping station 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 source (irrigation water tank), the model gives preference to the irrigation services.

5.1.1 Precipitation and evaporation

Some of the inputs for the water module are the precipitation and evaporation hourly data (see Figure 19). This input is given to the model in meters per hour (m/h). The precipitation [31] and evaporation [32] data that are used for this research are obtained from the hourly time-averaged 2-dimensional data collection in Modern-Era Retrospective analysis of Research and Applications version 2(MERRA-2), which is provided by the Global Modelling and Assimilation Office (GMAO). For the precipitation, the variable extracted from the data collection was the bias-corrected total precipitation (kg/m^2/s). The data set begins on 01-01-1980 and it has a spatial resolution of 0.5 x 0.625° [31]. For the evaporation, the variable extracted from the data collection was surface evaporation (kg/m2/s). The data set contains values from 01-01-1979 to 29-02-2016, and it has a spatial resolution of 0.5 x 0.667° [32].

The maximum and minimum accumulated annual precipitation are 1,726.42 mm and 634.39 mm. They were registered in 1992 and 2015, respectively (see Figure 20).

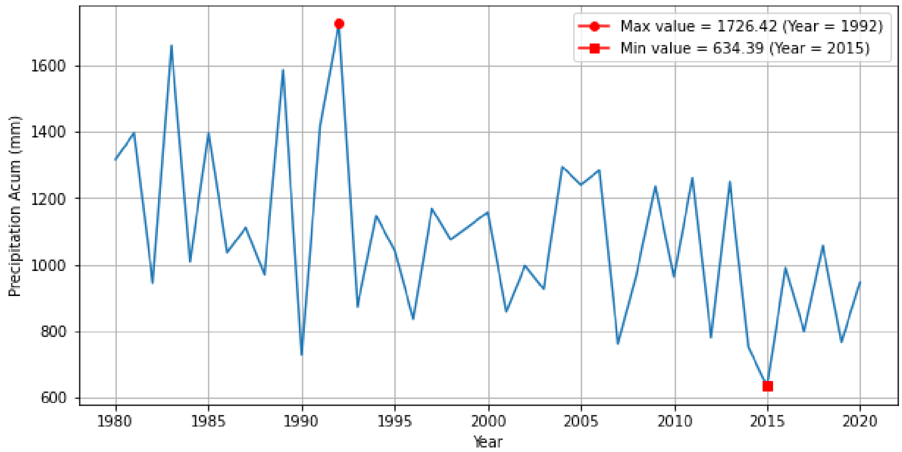

Figure 20. Anual accumulated precipitation from 1980 to 2020 on Caye Chapel [31].

The maximum and minimum accumulated annual evaporation are 1,713.68 mm and 1,343.78 mm. They were registered in 2001 and 1981, respectively (see Figure 21).

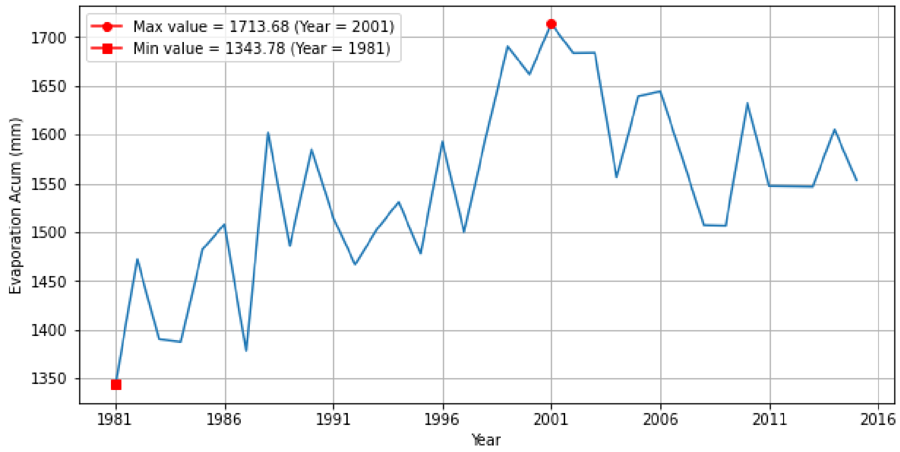

Figure 21. Anual accumulated evaporation from 1981 to 2015 on Caye Chapel [32].

The National Meteorological Service of Belize (NMSB) has two meteorological stations close to Caye Chapel, PGIA, and Municipal (see Figure 22). Their measurements are not used for this research because they do not have enough hourly precipitation data. Besides, they do not have a register for hourly evaporation measurements. Station PGIA started to register the hourly measurements in August 2015, and station Municipal began to record the hourly measurements in November 2017. A comparison of the annual accumulated precipitation for 2018, 2019, and 2020 shows that the GMAOs have an average variation of 36.94% ± 15.87%, relative to the data from the Municipal's meteorological station (see Table 13).

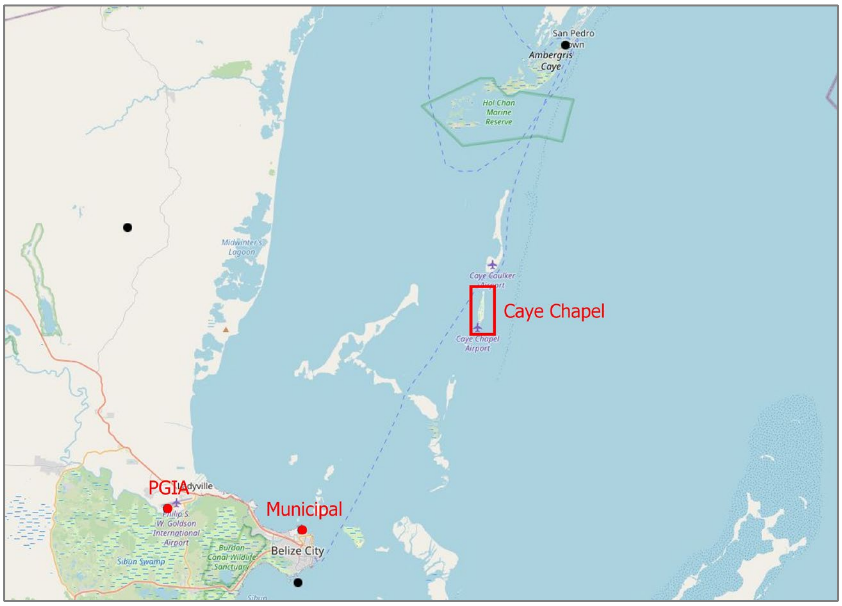

Figure 22. Location of the meteorological stations Municipal and PGIA [33].

Table 13. Comparison between the annual accumulated precipitation from the GMAO data collection and the meteorological station Municipal.

Source	Annual accumulated Precipitation (mm)					
	2018	2019	2020			
GMAO	1,057.38	767.04	947.41			
Municipal	1,503.40	1,036.60	2,111.80	*Average*	*STD*	*RSD*
Difference (%)	29.67%	26.00%	55.14%	*36.94%*	*15.87%*	*0.43*

5.1.2 Inhabitants and irrigation water demand

The water demand for Caye Chapel is divided into two types, the inhabitants' demand and the irrigation demand. In this research, the inhabitants' demand is defined as the water demanded by the population and the pools, and it does not include the water demand for HVAC systems. This demand must be satisfied with potable water. The irrigation demand is the amount of water required to irrigate the golf course and other areas around the island. The water used for these purposes can be potable, treated wastewater, treated rainwater, or a mixture of them. Table 14 shows the average daily demand for Caye Chapel. It is observed that the irrigation demand represents 62% of the daily demand, while the inhabitant's water demand represents 38% of it. The exact water demand values are shown in Appendix I.

Table 14. 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
Population water demand		1,397.75
Guest		376.00
Residents		909.60
Visitants		50.50
Workers		61.65
Pool water demand		15.83
Irrigation water demand	62%	2,333.00
Total	*100%*	*3,746.58*

Inhabitants' water demand patterns:

For this research, the inhabitants' water demand has constant hourly and monthly variations for any day and year, respectively. The hourly peak factors (see Table 15) are obtained from GFA Grupo Inmobiliario SC (personal communication, December 9, 2021). In Table 15 it is observed that the maximum hourly inhabitants' demand occurs between 16:00 and 18:59 hrs. The island developers proposed those factors, and it has no background on actual measurements from Caye Chapel. The monthly factors (see Table 16) are estimated for this research using the statistics for the total tourist arrival to Belize [34–36]. The detailed calculations are shown in Appendix III. The total tourist arrivals to Belize include American, European, Canadian, and Latin American tourist arrivals. In Table 16, the months with higher peak factors are March and December, while the lowest values are observed in September and October.

Table 15. Hourly peak factors for the inhabitants' water demand (source: GFA Grupo Inmobiliario SC, personal communication, December 9, 2021).

Hour	Hourly Peak Factor	Hour	Hourly Peak Factor
0	0.30	12	1.65
1	0.30	13	1.65
2	0.30	14	1.65
3	0.30	15	1.75
4	0.30	16	1.85
5	0.30	17	1.85
6	1.00	18	1.85

7	1.00	19	1.33
8	1.00	20	0.80
9	1.00	21	0.55
10	1.00	22	0.30
11	1.65	23	0.30

Table 16. Monthly peak factors for the inhabitants' water demand.

Month	Peak factor
January	1.16
Febraury	1.17
March	1.42
April	1.03
May	0.90
June	1.07
July	1.11
August	0.81
September	0.47
October	0.60
November	0.94
December	1.32

Irrigation water demand pattern:

The irrigation water demand pattern is constant throughout the time. The irrigation demand is not affected by the hourly's and monthly's peak factors described before (see Table 15 and Table 16). For this research, the daily irrigation is done over 6 hours from 01:00 to 06:00 hours on any day of the year. The peak factors for the irrigation demand are shown in Table 17.

Table 17. Hourly peak factors for the irrigation demand.

Hour	Hourly Peak Factor	Hour	Hourly Peak Factor
0	0.00	12	0.00
1	0.17	13	0.00
2	0.17	14	0.00
3	0.17	15	0.00
4	0.17	16	0.00
5	0.17	17	0.00
6	0.17	18	0.00
7	0.00	19	0.00
8	0.00	20	0.00
9	0.00	21	0.00
10	0.00	22	0.00
11	0.00	23	0.00

5.1.3 Drinking water treatment plant

The drinking water treatment plant (DWTP) simulates a desalination facility that uses reverse osmosis (RO) supplemented with an energy recovery device (ERD) to produce potable water from the seawater. This element is programmed to produce potable water every day between 02:00 and 23:59 hrs. The amount of potable water produced every hour can be between 0 and the DWTP maximal capacity. The amount of potable water produced every hour is limited by the available storage volume from te drinking water storage tank (DWT). On one hand, according to Greco et al. [37] the power consumption of an RO desalination plant can be reduced up to 2-2.50 kWh per cubic meter of potable water produced when the system uses an ERD. On the other hand, Nassrullah et al. [38] mention that the energy required to obtain one cubic meter of drinking water by treating seawater with RO is in the range of 4-6 kWh with an ERD. The parameters modeled for this element are described in Table 18.

Table 18. Parameters modeled for the drinking water treatment plant (DWTP).

Element	Drinking water treatment plant
Nomenclature	DWTP
Alternatives	All of them
Capacity	120 m^3/h (A2, A4, A6, A7, A9, A11) 170 m^3/h (A1, A3, A5, A8, A10, A12) *(Capacity defined after the optimization, consult Chapter 6)*
Energy consumption	6 kWh/m^3 [38]

5.1.4 Drinking water storage tank

The drinking water storage tank (DWT) receives water from the DWTP and delivers water to the irrigation and recovery water storage tank (IWT) or to the potable water services representing the inhabitants' water demands. The amount of water that comes into the DWT depends on the available storage volume at the beginning of each time step and the maximum water production capacity from the DWTP. The water that is pumped to the potable water services depends on the hourly inhabitants' water demand, the available stored water at the beginning of each time step, and the capacity of the pumping station no. 2 (see section 5.1.12). The amount of water that is pumped into the IWT depends on the IWT's available storage capacity, the percentage of stored water in the IWT (see section 5.1.7), the available DWT's stored water at the beginning of each time step, the percentage of stored water in the DWT, and the capacity of the pumping station no. 1 (see section 5.1.12). When the DWT's stored volume is below 30% of the maximum storage capacity, the model shuts down the pumping station no. 2 to safeguard the potable's water availability for the inhabitants' demand. At the end of every time step, the model performs a water balance between the inflow and outflow to calculate the new stored water volume for the next time step. The characteristics modeled for the DWT are shown in Table 19.

Table 19. Parameters modeled for the drinking water storage tank (DWT).

Element	Drinking water storage tank
Nomenclature	DWT
Alternatives	All of them
Capacity	3,800 m^3 *(Capacity defined after the optimization, consult Chapter 6)*

5.1.5 Wastewater treatment plant

The wastewater treatment plant (WWTP) simulates a Nereda® plant that uses aerobic granular sludge (AGS) technology to treat the wastewater. The water that goes into the WWTP is the water that was pumped from the DWT to the potable water services by the pumping station no. 2. However, not all drinking water becomes wastewater. It is assumed that only 85% becomes wastewater and the other 15% are losses due to evaporation, leakages, and water consumption. Furthermore, there is an additional water loss during the treatment due to the water trapped in the sludge and evaporation. Therefore, the model assumes that for every cubic meter that goes into the WWTP, only 90% becomes treated water. It is considered that the water delivered from the DWT to the potable water services takes 2 hours to reach the WWTP and the WWTP requires 1 hour to treat the inflow.

The amount of water that can be treated is limited by the WWTP capacity. If the hourly inflow is higher than the hourly capacity, then the exceedance of wastewater is rejected and discharged. The treated wastewater is pumped into the treated wastewater storage tank (WWT). If the WWT has insufficient storage capacity to receive the water coming from the WWTP, the surplus water is spilled. According to Pronk et al. [39] an AGS plant have an energy consumption of about 0.17 kW per cubic meter of treated influent. The parameters modeled for the WWTP are shown in Table 20.

Table 20. Parameters modeled for the wastewater treatment plant (WWTP).

Element	Wastewater treatment plant
Nomenclature	WWTP
Alternatives	All of them
Capacity	150 m^3/h *(Capacity defined after the optimization, consult Chapter 6)*
Water losses before treatment	15%
Water losses during treatment	10%
Energy consumption	0.17 kWh/m^3 [39]

5.1.6 Treated wastewater storage tank

The treated wastewater storage tank (WWT) receives water from the wastewater treatment plant (WWTP) and delivers water to the irrigation and recovery water storage tank (IWT). The amount of water that comes into the WWT depends on the available water storage volume at the beginning of the time step and the amount of water delivered by the WWTP. The water that is pumped into the IWT depends on the IWT's available storage capacity, the percentage of stored water in the IWT (see section 5.1.7), the available WWT's stored water at the beginning of each time step, and the capacity of the pumping station no. 4 (see section 5.1.12). When the inflow is higher than the available storage capacity, surplus treated wastewater is spilled. At the end of every time step, the model performs a water balance between the inflow and outflow to calculate the new stored water volume for the next time step. The parameters modeled for the WWT are shown in Table 21.

Table 21. Parameters modeled for the treated wastewater storage tank (WWT).

Element	Treated wastewater storage tank
Nomenclature	WWT
Alternatives	A2, A4, A6, A7, A9, A11
Capacity	500 m^3 *(Capacity defined after the optimization, consult Chapter 6)*

5.1.7 Irrigation and recovery water storage tank

The irrigation and recovery water storage tank (IWT) can receive water from three different sources: 1) from the drinking water storage tank (DWT) (applies for all the alternatives), 2) from the treated wastewater storage tanks (WWT) (applies for alternatives A2, A4, A6, A7, A9, A11), and/or 3) from the treated rainwater storage tank (RWT) (applies for alternatives A6 to A12). It delivers water to the irrigation system to satisfy the irrigation demand and to the water bodies (WB) to maintain the set water level. The amount of water that comes into the IWT is determined by the outflow conditions from the DWT (see section 5.1.4), WWT (see section 5.1.6), RWT (see section 5.1.10), and the available water storage capacity at the beginning of the time step. If the IWT is storing less volume than 50% of its capacity, it can receive water from all the sources. Otherwise, it can only receive water from the WWT and

RWT. This condition exists to give preference to the usage of treated water for irrigation purposes over drinking water. When the incoming water is greater than the available storage capacity, surplus water is spilled.

The amount of water that is pumped into the irrigation system depends on the hourly irrigation water demand, the available stored water at the beginning of the time step, and the capacity of the pumping station no. 8 (see section 5.1.12). The volume of water that is pumped to the WB depends on the available stored water in the IWT at the beginning of the time step, its percentage of stored water, the required amount of water from the WB to maintain their set level, and the capacity of the pumping station no. 9 (see section 5.1.12). In addition, the model does not deliver water to the WB when the percentage of water volume in the IWT is below 50%. This condition exists to give preference to the irrigation water demand over the WB water demand. Also, the model shut down the irrigation system when the hourly precipitation is higher than 1 mm/hr. The last is because the irrigation system is supposed to work 6 hours per day and according to the reference value provided by the Building Code from the Distrito Federal (Mexico) [40] the minimum irrigation demand must be 5 L/m^2/day (5 mm/m^2/day) for open areas. Those 5 mm distributed over 6 hours are 0.83 mm ~ 1 mm. At the end of every time step, the model performs a water balance between the inflow and outflow to calculate the new stored water volume for the next time step. The parameters modeled for the IWT are shown in Table 22.

Table 22. Parameters modeled for the treated irrigation and recovery water storage tank (IWT)

Element	Irrigation and recovery water storage tank
Nomenclature	IWT
Alternatives	All of them
Capacity	3,000 m^3 *(Capacity defined after the optimization, consult Chapter 6)*

5.1.8 Water bodies

The water bodies (WB) from the golf course are simulated as a single water body with a constant area among its entire depth. The WB can receive water from the IWT and from the precipitation. It loses water due to overflow events and evaporation. The model makes a water balance at the beginning of each time step between the inflow and outflow from the previous time step to determine the new water level. The new water level determines if the system must overflow or if it needs water. The water from the WB overflows when the water level is higher than the overflow level. The overflow goes to the rainwater buffer tank (RWB) in alternatives that consider rainwater harvesting (A7 to A12), and it is spilled in alternatives that do not consider rainwater harvesting (A1 to A6). The WB requires water to keep the water level at least on the set level. Therefore, when the water level is under the set level, the model will set the request for recovery water. The amount of water that goes into the WB depends on the requested volume and the outflow restrictions from the IWT (see section 5.1.7). The parameters modeled for the IWT are shown in Table 23.

Table 23. Parameters modeled for the water bodies (WB).

Element	Water bodies
Nomenclature	WB
Alternatives	All of them
Area	41,121 m^2
Set water level	1.40 m
Overflow water level	1.60 m

5.1.9 Rainwater buffer tank

The rainwater buffer tank (RWB) receives water from the water bodies' (WB) overflow and delivers water to the rainwater treatment plant (RWTP). The amount of water coming into the RWB depends on the available water storage volume at the beginning of the time step and the volume of water that overflows from the WB. The amount of water that is pumped into the RWTP depends on the maximum hourly water treatment capacity. When the inflow is higher than the available storage capacity, surplus rainwater is spilled. At the end of every time step, the model performs a water balance between the inflow and outflow to calculate the new stored water volume for the next time step. The parameters modeled for the RWB are shown in Table 24.

Table 24. Parameters modeled for the rainwater buffer tank (RWB).

Element	Rainwater buffer tank
Nomenclature	RWB
Alternatives	A7 to A12
Capacity	50 m^3 (A10, A12) 250 m^3 (A7-A9, A11) *(Capacity defined after the optimization, consult Chapter 6)*

5.1.10 Rainwater treatment plant

The rainwater treatment plant (RWTP) simulates a treatment scheme integrated by screening, coagulation and flocculation, sedimentation lane, rapid sand filters (RSF), and disinfection with chlorine. The water that goes into the RWTP is delivered by the rainwater buffer tank (RWB). The model considers water losses during the process due to the water that is trapped in the sludge and evaporation. Therefore, the model assumes that for every cubic meter that goes into the RWTP, only 95% becomes treated water. It is considered that the RWTP requires 1 hour to treat the inflow. The amount of water that can be treated is limited by the RWTP's capacity. All the treated rainwater is pumped into the treated rainwater storage tank (RWT). If the RWT has insufficient storage capacity to receive the water coming from the RWTP, then the surplus water is spilled. According to Arkhangelsky et al. [41] when the rapid sand filtration is performed with a pressure head up to 4 meters it requires up to 0.2 $kWh/m^{3,}$ including the energy for backwashing. In addition, the coagulation and flocculation process can demand between 0.2 to 0.4 kWh/m^3. The parameters modeled for the WWTP are shown in Table 25.

Table 25. Parameters modeled for the rainwater treatment plant (RWTP).

Element	Rainwater treatment plant
Nomenclature	RWTP
Alternatives	A7 to A12
Capacity	150 m^3/h (A8) 200 m^3/h (A10, A12) 300 m^3/h (A7, A9, A11) *(Capacity defined after the optimization, consult Chapter 6)*
Water losses during treatment	5%
Energy consumption	0.40 kWh/m^3 [41]

5.1.11 Treated rainwater storage tank

The treated rainwater storage tank (RWT) receives water from the rainwater treatment plant (RWTP) and delivers water to the irrigation and recovery water storage tank (IWT). The amount of water that comes into the RWT depends on the available water storage volume at the beginning of the time step and the amount of water delivered by the RWTP. The water that is pumped into the IWT depends on the IWT's available storage capacity, the percentage of stored water in the IWT (see section 5.1.7), the available RWT's stored water at the beginning of each time step, and the capacity of the pumping station no. 6 (see section 5.1.12). When the inflow is higher than the available storage capacity, surplus treated rainwater is spilled. At the end of every time step, the model performs a water balance between the inflow and outflow to calculate the new stored water volume for the next time step. The parameters modeled for the RWT are shown in Table 26.

Table 26. Parameters modeled for the rainwater storage tank (RWT).

Element	Treated rainwater storage tank
Nomenclature	RWT
Alternatives	A7 to A12
Capacity	30 m^3 *(Capacity defined after the optimization, consult Chapter 6)*

5.1.12 Pumping stations

This section describes the flows associated with each pumping station, the alternatives that consider them, the criteria used to determine their capacities, and their operation curves. Depending on the alternative, the water system can have up to nine (9) pumping stations. The modeled pumping stations do not change their capacities among the different alternatives. The flows associated with each pumping station are shown in Table 27.

Table 27. Pumping stations' flow directions.

Pumping station	**Associated flow**		**Alternative**
	From	**To**	
1	DWT	IWT	A1 - A12
2	DWT	Potable water services	A1 - A12
3	WWTP	WWT	A2, A4, A6, A7, A9, A11
4	WWT	IWT	A2, A4, A6, A7, A9, A11
5	RWB	RWTP	A7 - A12
6	RWTP	RWT	A7 - A12
7	RWT	IWT	A7 - A12
8	IWT	Irrigation system	A1 - A12
9	IWT	WB	A1 - A12

The total head (H) for each pumping station is calculated based on the architecture, landscape, and topographic conditions of Caye Chapel. The operation head (H_{op}) for the irrigation system is 35 m, for the potable water services is 40 m, and for transferring water between tanks and/or water treatment facilities, it is 15 m. The total head (H) calculation for each pumping station is shown in Table 28.

The design flows for each pumping station are determined by using the water balances from the model of alternative A9 under the meteorological conditions from the year 1992. The maximum, minimum, and mean hourly flows, excluding hours with flows equal to zero. Based on those flows, the maximum pumping capacity is determined and the number of pumps for every pumping station (see Table 28). The number of pumps that operate per hour is shown in Figure 23.

Table 28. Pumping stations' characteristics.

Pumping Station	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
DIRECTION									
From	DWT	DWT	WWTP	WWT	RWB	RWTP	RWT	IWT	IWT
To	IWT	Pot serv	WWT	IWT	RWTP	RWT	IWT	Irrig sys	WB
CHARACTERISTICS									
Pipe length (m)	103.20	2,375.00	23.20	113.20	23.20	23.20	48.20	2,360.00	
horizontal	100.00	2,375.00	20.00	110.00	20.00	20.00	45.00	2,360.00	1,250.00
vertical	3.20	0.00	3.20	3.20	3.20	3.20	3.20	0.00	0.00
Friction losses (%)	8%	0.3%	8%	8%	8%	8%	8%	0.3%	0.3%
HEAD (m)									
Suction - H_s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Height - H_d	3.20	3.08	3.20	3.20	3.20	3.20	3.20	3.08	3.08
z_1 =	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42
z_2 =	4.62	4.50	4.62	4.62	4.62	4.62	4.62	4.50	4.50
Friction - H_f	8.26	7.13	1.86	9.06	1.86	1.86	3.86	7.08	0.00
Operation - H_{op}	15.00	40.00	15.00	15.00	15.00	15.00	15.00	35.00	15.00
Total head - H	26.46	50.21	20.06	27.26	20.06	20.06	22.06	45.16	19.08
FLOW REMOVING HOURS WITH FLOWS EQUAL TO ZERO (m^3/hr)									
Max	97.21	154.73	118.37	315.00	60.00	47.50	215.00	388.83	1,300.00
Mean	97.14	58.89	45.05	46.13	28.17	26.07	32.23	294.43	859.43
Min	12.59	2.71	2.08	1.33	0.19	0.18	0.18	14.55	448.50
PUMING STATION SET-UP									
Pump capacity (m^3/h)	100.00	40.00	40.00	40.00	20.00	20.00	60.00	200.00	100.00
No. Pumps	1	4	3	4	3	3	2	2	1
Total capacity (m^3/h)	100.00	160.00	120.00	160.00	60.00	60.00	120.00	400.00	100.00
Head (m)	26.46	50.21	20.06	27.26	20.06	20.06	22.06	45.16	19.08
Efficiency	0.65	0.65	0.60	0.65	0.60	0.60	0.65	0.65	0.65

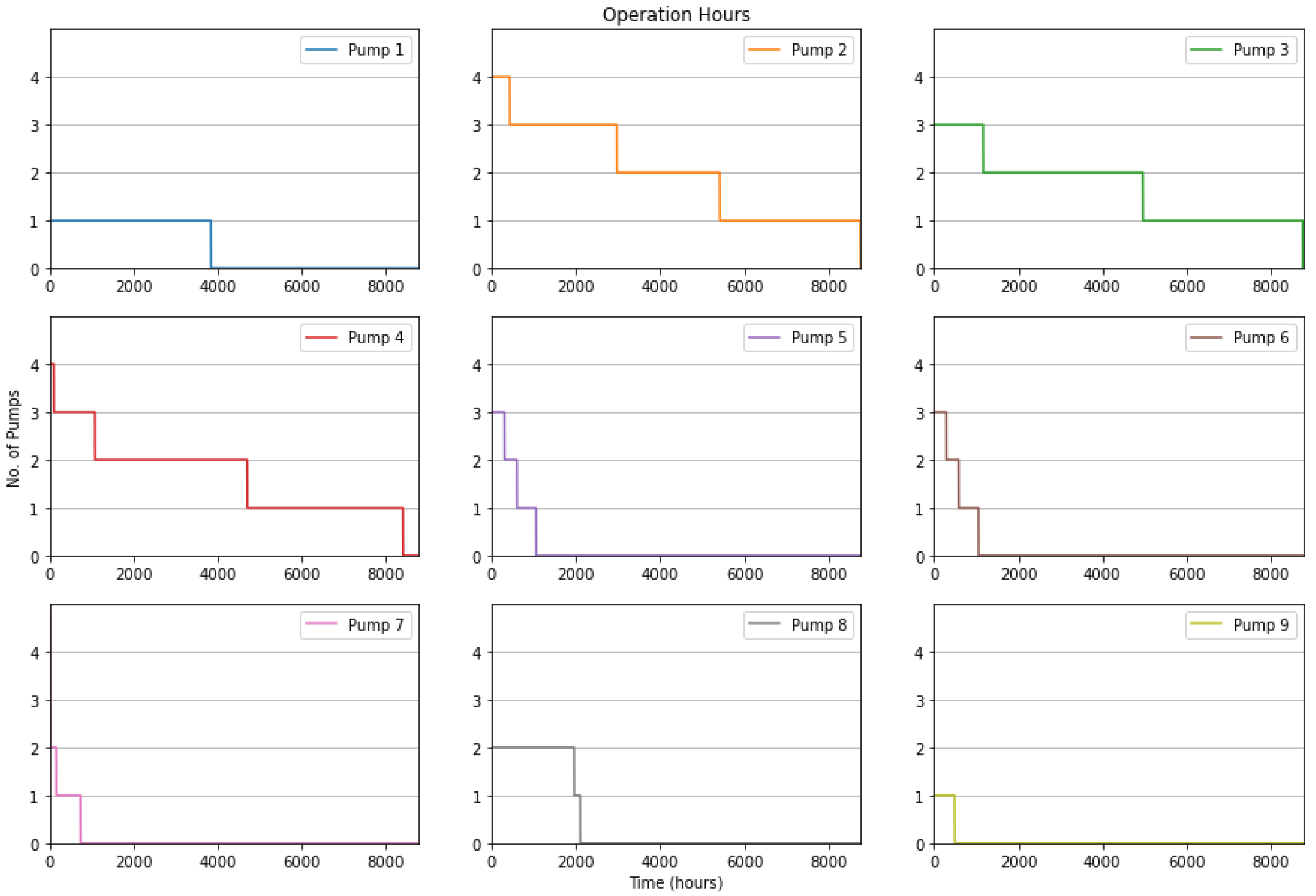

Figure 23. Operating hours for the 9 pumping stations using the model for alternative A9 under the meteorological conditions of 1992.

The operation curves for every pumping station are obtained from EPANET 2.2 [42] using the individual pump capacity and total head from Table 28. The operation curves for each pumping station are:

$$H_{pump\ no.1} = 35.28 - 0.0008821\ (Q)^2$$

$$H_{pump\ no.2} = 66.95 - 0.01046\ (Q/4)^2$$

$$H_{pump\ no.3} = 26.75 - 0.00418\ (Q/3)^2$$

$$H_{pump\ no.4} = 36.35 - 0.00568\ (Q/4)^2$$

$$H_{pump\ no.5} = 26.75 - 0.01672\ (Q/3)^2$$

$$H_{pump\ no.6} = 26.75 - 0.01672\ (Q/3)^2$$

$$H_{pump\ no.7} = 29.41 - 0.002043\ (Q/2)^2$$

$$H_{pump\ no.8} = 60.21 - 0.0003764\ (Q/2)^2$$

$$H_{pump\ no.9} = 25.44 - 0.0006361\ (Q)^2$$

(1)

The hourly energy consumption per pumping station is defined as follows:

$$E_{pump} = \frac{1{,}000\ kg \cdot m^{-3} \cdot h^{-1}}{(3{,}600\ s \cdot hr^{-1})(1{,}000\ W \cdot kW^{-1})} \cdot \frac{Q \cdot H_{pump} \cdot g}{\mu}$$

(2)

Where E_{pump} is the pumping station's hourly energy consumption (kW/h), Q is the hourly flow rate (m^3/h), g represents the gravity acceleration (m/s^2), and μ is the efficiency of the pumping station. The efficiency of each pumping station is shown in Table 28. It is observed that the pumps that work with lower water qualities have lower efficiencies.

5.1.13 Delays between elements

The model considers time delays between the elements that integrate the water module's elements. Table 29 shows the matrix of the delays between these elements. For example, the WWTP is one step ahead of itself, and the WB is two steps ahead of the IWT. This means that 1 m^3 coming into the WWTP will take one time step to go out of the WWTP, and 1 m^3 coming out from the WB will take three steps to go into the IWT.

Table 29. Delays between elements from the water module.

	DWTP	DWT	WWTP	WWT	WB	RWB	RWTP	RWT	IWT
DWTP	0	0	2	3	-	-	-	-	-
DWT	0	0	2	3	-	-	-	-	-
WWTP	-2	-2	1	0	-	-	-	-	-
WWT	-3	-3	0	0	-	-	-	-	-
WB	-	-	-	-	0	1	1	2	2
RWB	-	-	-	-	-1	0	0	1	1
RWTP	-	-	-	-	-1	0	1	0	1
RWT	-	-	-	-	-2	-1	0	0	0
IWT	-	-	-	-	-2	-1	-1	0	0

5.2 Energy module

This section presents the elements from the energy module. It describes how the elements are integrated into the model and how they work. The elements inside the energy module are the technologies for renewable electricity production and storage. The input data for the energy module is the hourly wind speed and/or solar irradiance hourly data and the electricity demand from the urban water cycle. In this module, 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 met 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 surplus energy can be stored when there is available capacity in the energy storage technology or 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.

5.2.1 Wind speed and solar irradiance

Some of the inputs for the energy module are the wind speed [31] and solar irradiance [43] hourly data (see Figure 19). These inputs must be given to the model in meters per second (m/s) for the wind speed and watts per square meter (W/m^2) for the solar irradiance. For this research, the data set for the wind speed and solar irradiance is obtained from the hourly time-averaged 2-dimensional data collection in Modern-Era Retrospective analysis of Research and Applications version 2(MERRA-2), which is provided by the Global Modelling and Assimilation Office (GMAO). For the windspeed, the variable extracted from the data collection was the surface wind speed (m/s). The data represents the wind speed at 10 m above the surface. The data set begins on 01-01-1980, and it has a spatial resolution of 0.5 x 0.625° [31]. For the solar irradiance, the variable extracted from the data collection was the incident short wave land (W/m^2). The data set begins on 01-01-1980 and it has a spatial resolution of 0.5 x 0.625°[43].

Figure 24 shows the 90th percentile for the windspeed from 1980 to 2020. The maximum value is modeled in 1991 as 8.01 m/s. The minimum value is m

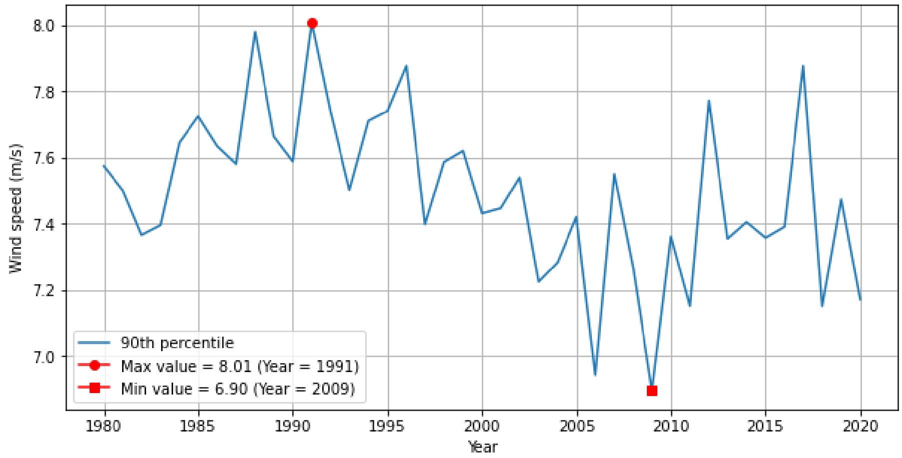

Figure 24. Wind speed's 90th percentile from 1980 to 2020 on Caye Chapel [31].

Figure 25 shows the maximum and minimum yearly accumulated solar irradiance are 2,257.57 kW/m^2 and 1,953.29 kW/m2. They were registered in 1999 and 1992, respectively.

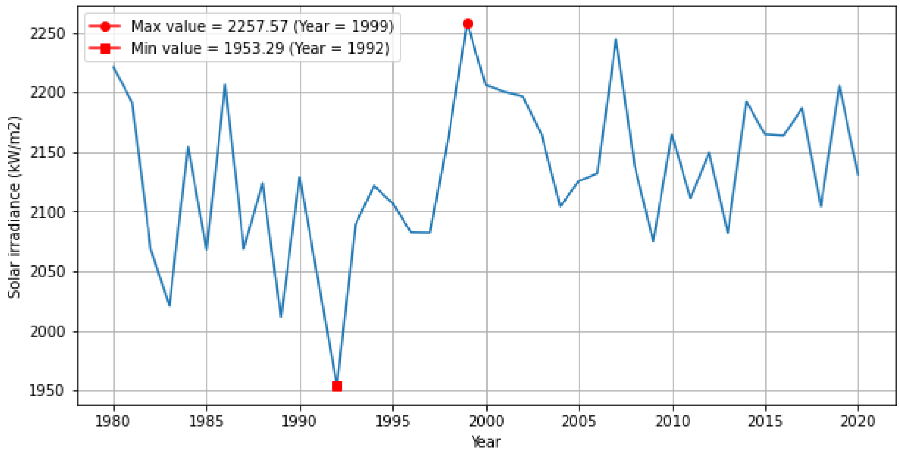

Figure 25. Anual accumulated solar irradiance from 1980 to 2020 on Caye Chapel [43].

5.2.2 Wind turbines

The wind turbines (WT) simulate electricity production using the wind as a renewable resource. This element receives as input the hourly wind speed data at the height of 10 m above the surface and gives as output electricity that can be supplied to the urban water cycle, stored, or rejected. The model translates the wind speed at 10 m to a wind speed at the hub's height to define how much electricity is produced. Then, it translates the wind speed to electricity production using a rated power curve determined by the wind turbine itself. According to Amponsah et al. [44], offshore wind turbines' life cycle GHG emissions are 13.0 ± 5.2 gCO_2-eq kW/h of electricity.

The wind speed at 10 m is translated to the wind speed at the turbines hub height as follows [6]:

$$v_z = v_{10} \cdot \left(\frac{z}{10}\right)^{0.14} \tag{3}$$

Where v_z is the wind speed at the hub's height (m/s), v_{10} is the wind speed at 10 meters above the surface (m/s), and z is the hub's height relative to the surface (m).

The rated power curve used in the model is generic and is obtained from the Danish Energy Agency and Energinet [45]. Figure 26 shows that the WT has a cut in at 5 m/s. It reaches the rated power at 12 m/s and has a cut out at 25 m/s. Above 30 m/s the WT does not produce electricity. The function that describes the electricity production is:

$$v_z \in [0,5] \cup (30,\infty) \ \rightarrow E_{wind}(v_z) = 0$$
$$v_z \in (5,12) \rightarrow E_{wind}(v_z) = P(v_z - 5)/7$$
$$v_z \in [12,25) \rightarrow E_{wind}(v_z) = P_{wind}$$
$$v_z \in [25,30] \rightarrow E_{wind}(v_z) = P_{wind}(6 - v_z/5)$$

(4)

Where E_{wind} is the renewable electricity production (kW), and P_{wind} is the wind turbine's rated power.

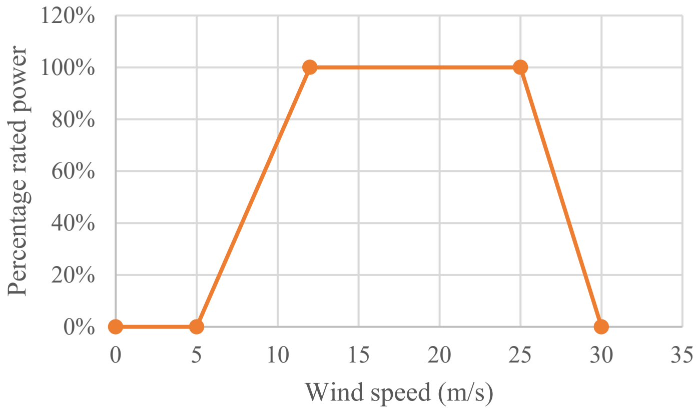

Figure 26. Rated power curve for the wind turbines in the energy module.

The parameters modeled for the WT are shown in Table 30.

Table 30. Parameters modeled for the wind turbines (WT).

Element	Wind turbine
Nomenclature	WT
Alternatives	A1 to A4 and A7 to A10
Rated power	3,000 kW
Hub's height	100 m
Number of wind turbines	1 (A3, A4, A9, A10) 2 (A1, A2, A7, A8)
CO_2-eq emissions	13 g CO_2-eq kW/h of electricity

5.2.3 PV panels

The PV panels (PV) simulate the energy production from solar energy. This element receives as input the hourly solar irradiance and gives as output and hourly electricity production. The electricity produced can be supplied to the urban water cycle, stored, or rejected. According to Amponsah et al. [44], the life cycle GHG emissions for the offshore crystalline silicone (c-Si) systems range from 9.4 to 300 (mean 91.1) gCO_2-eq kW/h of electricity. The amorphous silicon (a-Si) systems have lower emissions. However, the last is used as a photovoltaic solar cell material for applications requiring little power [46].

The module converts solar irradiance into electricity production as follows [45]:

$$E_{solar} = H_{solar} \cdot A \cdot Y \cdot T_{factor} \cdot P_{factor}$$

(5)

Where the E_{solar} is the electricity produced by the PV panels (kW), H_{solar} is the solar irradiance (kW/m^2), A is the PV panels area (m^2), Y is the yield for the PV panels, T_{factor} is the transposition factor, and P_{factor} is the performance factor where the losses of energy are considered. The parameters modeled for the PV are shown in Table 31.

Table 31. Parameters modeled for the PV panels (PV).

Element	PV panels
Nomenclature	PV
Alternatives	A3 to A6 and A9 to A12
Area	4,000 m^2 (A3, A4, A9, A10) 7,000 m^2 (A5, A6, A11, A12)
Yield	0.20
Transposition factor	1.17
Performance factor	0.80
CO_2-eq emissions	91.1 g CO_2-eq kW/h of electricity

5.2.4 Battery

The battery (BT) simulates one unit of a lithium-ion battery from Samsung SDI E3-R135 [47]. These units have energy storage of 3.2 MWh, and an output and input capacity of 9.6 MW and 1.6 MW, respectively. This element receives electricity from the wind turbine(s) (WT) and/or the PV panels (PV), depending on the alternative. It delivers electricity to the urban water cycle when it is necessary. The model uses the electricity produced by the WT and PV to satisfy the urban water cycle's electricity demand. When the renewable electricity produced is smaller than the electricity demand, the BT delivers electricity to the urban water cycle's grid. The amount of electricity that the BT delivers depends on the amount of electricity demand that has not been satisfied by the current renewable electricity production and the amount of energy available in the BT. When the renewable electricity produced is greater than the electricity demand, the BT does not deliver electricity but can receive electricity and store it as energy. The amount of energy stored at every time step depends on the amount of renewable electricity surplus and the available storage capacity.

According to the Danish Energy Agency in their technology data catalogue for energy storage [47] the Lithium-ion NMC battery (Utility-scale, Samsung SDI E3-R135) has a charge and discharge efficiencies of 98% and 97%, respectively. Nevertheless, for this research, the efficiency considered for the battery is 90%. This efficiency is also considered in the H2RES model [7]. The model includes this efficiency in the BT's outlet, meaning that 1 kW of electricity is stored as 1 kW of energy, but 1 kW of energy is delivered as 0.90 kW of electricity. The life cycle GHG emissions considered for the battery are 74 g CO2-eq for providing storage capacity to 1 kWh of electricity [48]. The parameters modeled for the BT are shown in Table 32.

Table 32. Parameters modeled for the battery (BT).

Element	Battery
Nomenclature	BT
Alternatives	All of them
Capacity	3,200 kWh
Inlet capacity	1,600 kW
Outlet capacity	9,600 kW
Efficiency	0.90
CO_2-eq emissions	74 g CO_2-eq per stored kWh of electricity

5.2.5 Fossil energy

The model simulates the fossil energy supply as the shortage in the renewable energy supply. The model assumes that when the total or partial electricity demand from the urban water cycle is not satisfied by the wind turbines, PV panels, and/or stored energy, then it is met by fossil energy. For this research, it is considered that fossil energy comes from oil. The 2020 Belize's Annual Energy Report [49] explains that the primary fuel production in the country is dedicated to crude oil. Amponsah et al. [44] show that the estimates for Life Cycle GHG Emissions for electricity generation methods using oil as a source, generate 733 g CO_2-eq kW/h of electricity.

6 Multi-objective optimization

This chapter describes the optimization process that is performed over the twelve different alternatives, the elements that are optimized, the parameters that are minimized, and the results of the optimization.

6.1 Optimization process

The twelve alternatives are optimized 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 produce the minimum water demand shortage, the minimum amount of treated water that is not reused, and the renewable electricity shortage. The water demand shortage is an indicator of water security. The amount of treated water that is not reused is an indicator of the water system's efficiency. The ideal system would be the one that reuses all the water that it treats. The renewable electricity shortage is an indicator of energy security and clean energy. This process uses 36 years of hourly data (from 1981 to 2015) for precipitation, evaporation, wind speed, and solar irradiance as input for the model. The optimization is represented as follows:

$$
\begin{aligned}
&minimize:\\
&\qquad y_1 \;=\; mean\ water\ demand\ shortage\ (m^3/y)\\
&\qquad y_2 \;=\; mean\ treated\ water\ that\ is\ not\ reused\ (m^3/y)\\
&\qquad y_3 \;=\; mean\ renewable\ electricity\ shortage\ (kW/y)\\
&subject\ to:\\
&\qquad x_1 \in (1800, 2800, 3800)\\
&\qquad x_2 \in (100, 300, 500)\ *\\
&\qquad x_3 \in (50, 150, 250)\ **\\
&\qquad x_4 \in (100, 200, 300)\ **\\
&\qquad x_5 \in (1000, 2000, 3000)\\
&\qquad x_6 \in (50, 150, 250)\\
&\qquad x_7 \in (30, 60, 90)\ **\\
&\qquad x_8 \in (120, 170, 220)\\
&where:\\
&\qquad x_1 \;=\; drinking\ water\ storage\ tank\ capacity\ (m^3)\\
&\qquad x_2 = treated\ wastewater\ storage\ tank\ capacity\ (m^3)\\
&\qquad x_3 \;=\; rainwater\ buffer\ tank\ capacity\ (m^3)\\
&\qquad x_4 \;=\; treated\ rainwater\ storage\ tank\ capacity\ (m^3)\\
&\qquad x_5 \;=\; irrigation\ and\ water\ bodies\ recovery\ tank\ capacity\ (m^3)\\
&\qquad x_6 \;=\; wastewater\ treatment\ plant\ capacity\ (m^3/h)\\
&\qquad x_7 \;=\; rainwater\ treatment\ plant\ capacity\ (m^3/h)\\
&\qquad x_8 \;=\; drinking\ water\ treatment\ plant\ capacity\ (m^3/h)\\
\\
&*\ Only\ applies\ for\ alternatives\ 2, 4, 6, 7, 9, and\ 11.\\
&**\ Only\ applies\ for\ alternatives\ 7\ to\ 12.
\end{aligned}
\tag{6}
$$

There are three (3) values for each element (x). The middle values for each element (x) were determined through a design process using the model for alternative A9 and the hourly meteorological data from 1992. Alternative A9 was selected because it contains all the proposed elements for the water system. The meteorological conditions from

1992 correspond to the year with the maximum yearly accumulated precipitation. This research defines the low and high end of each set of values arbitrarily.

The middle values for the water storage tanks (*x_1 to x_5*) were determined as 20% or 30% of the maximum total daily demand for each water storage tank. This rule of thumb provides a sufficient balancing volume for a predominant household demand pattern [50]. Therefore, it cannot be used straightforward for the design of systems that satisfy touristic demand patterns. However, for this research, the middle value calculated from this rule of thumb is used as a starting point to proceed with the optimization process.

The middle value for the wastewater treatment plant (x_6) was defined from the maximum hourly wastewater discharge in one year. The middle value for the rainwater treatment plant (x_7) was defined using as a reference the average hourly rainwater discharge from the water bodies. Finally, the middle value for the drinking water treatment plant (x_8) was defined by the average daily demand divided by 10 which is the amount of hours that the desalination facility will operate per day (see section 5.1.3) .

6.2 Optimization results

The results of the multi-objective optimization process can be represented on a 3-dimensional plane, where each axis represents one of the optimization criteria. 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 (see Appendix IV). 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 capacities for the water storage tanks and water treatment facilities are shown in Table 33. The optimal solution for each alternative is defined as the closest one to the origin (0, 0, 0).

$$f(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8) = \text{minimize}\sqrt{{y_1}^2 + {y_3}^2 + {y_3}^2} \tag{7}$$

Table 33. Optimal capacities for the water storage tanks and water treatment facilities.

ALTERNATIVE	DWT	WWT	RWB	RWT	IWT	WWTP	RWTP	DWTP
1	3,800	-	-	-	3,000	150	-	170
2	3,800	500	-	-	3,000	150	-	120
3	3,800	-	-	-	3,000	150	-	170
4	3,800	500	-	-	3,000	150	-	120
5	3,800	-	-	-	3,000	150	-	170
6	3,800	500	-	-	3,000	150	-	120
7	3,800	500	250	300	3,000	150	30	120
8	3,800	-	250	100	3,000	150	30	170
9	3,800	500	250	300	3,000	150	30	120
10	3,800	-	50	200	3,000	150	30	170
11	3,800	500	250	300	3,000	150	30	120
12	3,800	-	50	200	3,000	150	30	170

7 Capital and operational costs

This chapter describes how capital and operational and maintenance (O&M) costs are estimated and for what elements from the water-energy system are estimated. Table 34 shows the elements for which the costs are calculated, their capacities, the number of elements, the capital cost, the operational and maintenance cost, and the alternatives for which they applied. In addition, there are notes for each element describing the source and particular considerations for the estimation of the costs.

Table 34. Captial and operational costs.

NO.	ELEMENT	CODE	CAP.	QTY	CAPIT. COST (EUR x10^3)	OPER. COST (EUR x10^3/year)	ALTERNATIVES												NOTE
							1	2	3	4	5	6	7	8	9	10	11	12	
WATER MODULE																			
Water Storage Tanks																			
1	Drinking Water Storage Tank (m^3)	DWT	3,800	1	2,129.66 €	109.96 €	x	x	x	x	x	x	x	x	x	x	x	x	A, C
2	Treated Wastewater Storage Tank (m^3)	WWT	500	1	464.13 €	24.18 €	-	x	-	x	-	x	x	-	x	-	x	-	A, C
3	Rainwater Buffer Tank (m^3)	RWB	50	1	82.31 €	12.48 €	-	-	-	-	-	-	-	-	-	x	-	x	A, C
4	Rainwater Buffer Tank (m^3)	RWB	250	1	275.75 €	17.68 €	-	-	-	-	-	-	x	x	x	-	x	-	A, C
5	Treated Rainwater Storage Tank (m^3)	RWT	100	1	138.54 €	13.78 €	-	-	-	-	-	-	-	x	-	-	-	-	A, C
6	Treated Rainwater Storage Tank (m^3)	RWT	200	1	233.19 €	16.38 €	-	-	-	-	-	-	-	-	-	x	-	x	A, C
7	Treated Rainwater Storage Tank (m^3)	RWT	300	1	316.22 €	18.98 €	-	-	-	-	-	-	x	-	x	-	x	-	A, C
8	Irrigation and Water Recovery Tank (m^3)	IWT	3,000	1	1,783.16 €	89.17 €	x	x	x	x	x	x	x	x	x	x	x	x	A, C
Water Treatment Plants																			
9	Wastewater Treatment Plant (m^3/h)	WWTP	150	1	5,000.00 €	-	x	x	x	x	x	x	x	x	x	x	x	x	B
10	Rainwater Treatment Plant (m^3/h)	RWTP	30	1	2.70 €	7.37 €	-	-	-	-	-	-	x	x	x	x	x	x	A

11	Drinking Water Treatment Plant (m^3/h)	DWTP	120	1	3,308.59 €	326.76 €	-	x	-	x	-	x	x	-	x	-	x		A
12	Drinking Water Treatment Plant (m^3/h)	DWTP	170	1	4,687.16 €	461.04 €	x	-	x	-	x	-	-	x	-	x	-	x	A
Pumping Stations																		
13	Pumping station 1 (m^3/h)	P1	100	1	583.06 €	28.04 €	x	x	x	x	x	x	x	x	x	x	x	x	A, C
14	Pumping station 2 (m^3/h)	P2	160	1	832.64 €	44.86 €	x	x	x	x	x	x	x	x	x	x	x	x	A, C
15	Pumping station 3 (m^3/h)	P3	80	1	492.32 €	22.43 €	x	x	x	x	x	x	x	x	x	x	x	x	A, C
16	Pumping station 4 (m^3/h)	P4	120	1	669.49 €	33.64 €	-	x	-	x	-	x	x	-	x	-	x	-	A, C
17	Pumping station 5 (m^3/h)	P5	60	1	395.85 €	16.82 €	-	-	-	-	-	-	x	x	x	x	x	x	A, C
18	Pumping station 6 (m^3/h)	P6	60	1	395.85 €	16.82 €	-	-	-	-	-	-	x	x	x	x	x	x	A, C
19	Pumping station 7 (m^3/h)	P7	240	1	1,132.28 €	67.28 €	-	-	-	-	-	-	x	x	x	x	x	x	A, C
20	Pumping station 8 (m^3/h)	P8	400	1	1,667.78 €	112.14 €	x	x	x	x	x	x	x	x	x	x	x	x	A, C
21	Pumping station 9 (m^3/h)	P9	100	1	583.06 €	28.04 €	x	x	x	x	x	x	x	x	x	x	x	x	A, C
ENERGY MODULE																		
22	Wind turbines (kW)	WT	3,000	1	6,360.00 €	150.00 €	-	-	x	x	-	-	-	-	x	x	-	-	D
23	Wind turbines (kW)	WT	3,000	2	12,720.00 €	300.00 €	x	x	-	-	-	-	x	x	-	-	-	-	D
24	PV panels (m^2)	PV	4,000	1	1,265.31 €	11.10 €	-	-	x	x	-	-	-	-	x	x	-	-	D
25	PV panels (m^2)	PV	7,000	1	2,214.29 €	19.43 €	-	-	-	-	x	x	-	-	-	-	x	x	D
26	Batteries (kW)	BT	3,200	1	3,334.40 €	1.73 €	x	x	x	x	x	x	x	x	x	x	x	x	E

NOTES:

A. The capital and operational costs for the water storage tanks and water treatment facilities are estimated using the tool CoP cost calculator [51]. The operational costs do not include the energy costs.

B. The capital cost for the Nereda plant is provided by Sjoerd Kerstens (personal communication, May 10, 2022), member of the Advisory Group Waste Water at Royal HaskoningDHV Nederland B.V.

C. The tool CoP cost calculator [51] provides the cost estimations for water storage tanks and pumping stations with a minimum capacity of 600 m^3 and 600 m^3/h, respectively. Therefore, for this study, the capital and operational costs are estimated by extrapolation from the cost of the tool CoP cost calculator (see Appendix V).

D. The capital and operational costs are obtained from the Technology Data Catalogue for Electricity Generation [45].

E. The capital and operational costs are obtained from the Technology Data Catalogue for Energy Storage [47].

8 Greenhouse gases emissions

The GHG emissions are calculated for the elements in the energy system. The values for the GHG emissions are described in Table 35. The total emissions per alternative for the years 1992 and 2015 are shown in Table 36.

Table 35. GHG emissions per energy source.

ELECTRICITY PRODUCTION	GHG EMISSIONS
Wind turbines	13 gCO_2-eq kW/h of electricity
PV panels	91.1 gCO_2-eq kW/h of electricity
Battery	74 gCO_2-eq per stored kWh of electricity
Fossil energy (oil)	733 gCO_2-eq kW/h of electricity

Table 36. Calculation of GHG emissions.

SCENARIO YEAR 1992

Alternatives	1	2	3	4	5	6	7	8	9	10	11	12
ELECTRICITY PRODUCTION												
Wind turbine energy production (kW/y)	13,988,766.81	13,988,766.81	6,994,383.40	6,994,383.40	0.00	0.00	13,988,766.81	13,988,766.81	6,994,383.40	6,994,383.40	0.00	0.00
PV panels energy production (kW/y)	0.00	0.00	2,139,090.59	2,139,090.59	3,743,408.53	3,743,408.53	0.00	0.00	2,139,090.59	2,139,090.59	3,743,408.53	3,743,408.53
Battery electricity delivered (kW/y)	865,176.06	852,916.69	778,212.95	782,323.57	537,319.92	839,109.44	853,216.66	864,911.78	782,679.95	777,660.37	837,635.03	536,175.74
Fossil energy production (kW/y)	3,014,886.01	1,849,882.21	2,345,845.71	1,100,470.43	4,936,954.14	2,880,197.08	1,861,008.42	3,029,065.35	1,112,129.47	2,361,335.62	2,898,872.26	4,958,121.14
CO2 EMISSIONS												
Wind turbines (ton CO2_eq/y)	181.85	181.85	90.93	90.93	0.00	0.00	181.85	181.85	90.93	90.93	0.00	0.00
PV panels (ton CO2_eq/y)	0.00	0.00	194.87	194.87	341.02	341.02	0.00	0.00	194.87	194.87	341.02	341.02
Battery (ton CO2_eq/y)	64.02	63.12	57.59	57.89	39.76	62.09	63.14	64.00	57.92	57.55	61.98	39.68
Fossil energy (ton CO2_eq/y)	2,209.91	1,355.96	1,719.50	806.64	3,618.79	2,111.18	1,364.12	2,220.30	815.19	1,730.86	2,124.87	3,634.30
TOTAL	***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

Alternatives	1	2	3	4	5	6	7	8	9	10	11	12
ELECTRICITY PRODUCTION												
Wind turbine energy production (kW/y)	13,988,766.81	13,988,766.81	6,994,383.40	6,994,383.40	0.00	0.00	13,988,766.81	13,988,766.81	6,994,383.40	6,994,383.40	0.00	0.00
PV panels energy production (kW/y)	0.00	0.00	2,370,461.86	2,370,461.86	4,148,308.25	4,148,308.25	0.00	0.00	2,370,461.86	2,370,461.86	4,148,308.25	4,148,308.25
Battery electricity delivered (kW/y)	864,601.80	852,723.00	788,595.38	786,011.12	661,145.83	903,759.95	852,723.00	864,601.80	786,011.12	788,595.38	903,759.95	661,145.83
Fossil energy production (kW/y)	3,017,343.47	1,852,413.32	2,235,917.43	1,032,787.86	4,638,724.39	2,715,625.90	1,852,413.32	3,017,343.47	1,032,787.86	2,235,917.43	2,715,625.90	4,638,724.39
CO2 EMISSIONS												
Wind turbines (ton CO2_eq/y)	181.85	181.85	90.93	90.93	0.00	0.00	181.85	181.85	90.93	90.93	0.00	0.00
PV panels (ton CO2_eq/y)	0.00	0.00	215.95	215.95	377.91	377.91	0.00	0.00	215.95	215.95	377.91	377.91
Battery (ton CO2_eq/y)	63.98	63.10	58.36	58.16	48.92	66.88	63.10	63.98	58.16	58.36	66.88	48.92
Fossil energy (ton CO2_eq/y)	2,211.71	1,357.82	1,638.93	757.03	3,400.18	1,990.55	1,357.82	2,211.71	757.03	1,638.93	1,990.55	3,400.18
TOTAL	***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***

9 Electricity demand

The monthly average urban water cycle’s electricity demand is 587.69 ± 103.94 MW/month. Table 37 shows the monthly average electricity consumption for the pumping stations, water treatment plants, and other services. The other services are out of the scope of this research and represent the different buildings and amenities in the island, excluding HVAC systems and machinery rooms. Further, details on those calculations are shown in Appendix VI. Table 38, Figure 27, and Figure 28 show the percentages of electricity consumption for the urban water cycle and other services.

Table 37. Monthly average electricity consumption for the elements in the urban water cycle and other services (using a sample of 35 years).

	ELECTRICITY DEMAND (MW/month)													
ALTERNATIVE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	***AVERAGE***	***STD***
Urban Water Cycl	687.36	488.66	687.36	488.66	687.36	488.66	487.70	687.03	487.70	687.06	487.70	687.06	***587.69***	*103.94*
Pumping stations	35.95	39.97	35.95	39.97	35.95	39.97	40.10	36.00	40.10	36.00	40.10	36.00	*38.01*	*2.12*
Pump 1	6.31	2.64	6.31	2.64	6.31	2.64	2.62	6.30	2.62	6.30	2.62	6.30	*4.47*	*1.92*
Pump 2	13.85	13.85	13.85	13.85	13.85	13.85	13.85	13.85	13.85	13.85	13.85	13.85	*13.85*	*0.00*
Pump 3	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	*4.56*	*0.00*
Pump 4	0.00	6.07	0.00	6.07	0.00	6.07	6.05	0.00	6.05	0.00	6.05	0.00	*3.03*	*3.16*
Pump 5	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.01	0.06	0.01	0.06	0.01	*0.02*	*0.02*
Pump 6	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.01	0.05	0.01	0.05	0.01	*0.02*	*0.02*
Pump 7	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.02	0.04	0.01	0.04	0.01	*0.01*	*0.02*
Pump 8	11.07	12.65	11.07	12.65	11.07	12.65	12.67	11.08	12.67	11.08	12.67	11.08	*11.87*	*0.83*
Pump 9	0.16	0.21	0.16	0.21	0.16	0.21	0.21	0.16	0.21	0.16	0.21	0.16	*0.18*	*0.03*
DWTP	679.22	480.52	679.22	480.52	679.22	480.52	479.34	678.83	479.34	678.87	479.34	678.87	*579.49*	*103.98*
WWTP	8.14	8.14	8.14	8.14	8.14	8.14	8.14	8.14	8.14	8.14	8.14	8.14	*8.14*	*0.00*
RWTP	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.06	0.22	0.05	0.22	0.05	*0.07*	*0.09*
Other Services	168.12	168.12	168.12	168.12	168.12	168.12	168.12	168.12	168.12	168.12	168.12	168.12	***168.12***	*0.00*
Island's demand (Urban water cycle + Other	*855.48*	*656.78*	*855.48*	*656.78*	*855.48*	*656.78*	*655.82*	*855.15*	*655.82*	*855.18*	*655.82*	*855.18*	***755.81***	*103.94*

Table 38. Percentage of the electricity consumption.

	PERCENTAGE ELECTRICITY CONSUMPTION													
ALTERNATIVE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	***AVERAGE***	***STD***
Urban Water Cycle	80.35%	74.40%	80.35%	74.40%	80.35%	74.40%	74.36%	80.34%	74.36%	80.34%	74.36%	80.34%	77.36%	3.11%
Other Services	19.65%	25.60%	19.65%	25.60%	19.65%	25.60%	25.64%	19.66%	25.64%	19.66%	25.64%	19.66%	22.64%	3.11%
Island's demand (Urban water cycle + Other Services)	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%		

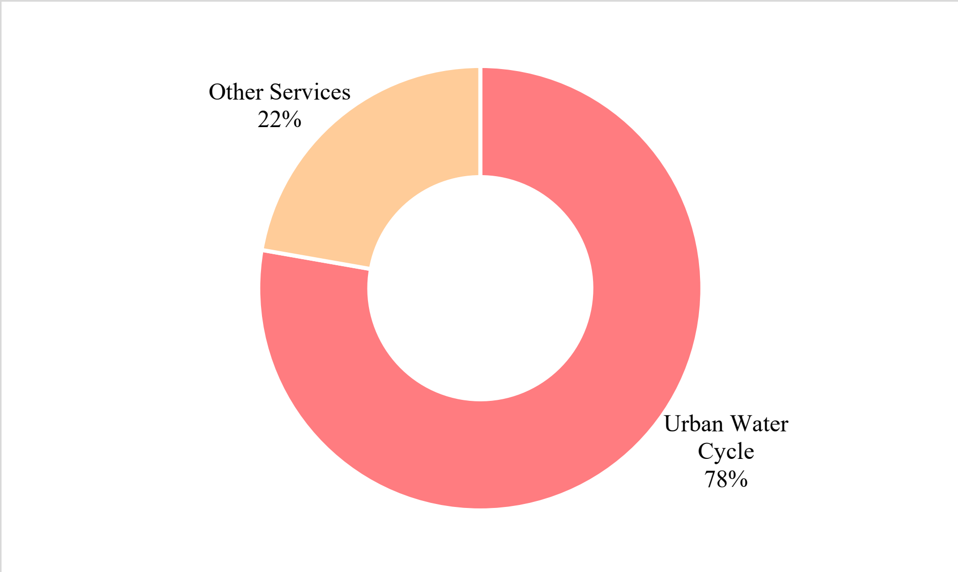

Figure 27. Average share of electricity consumption: urban water cycle and other services.

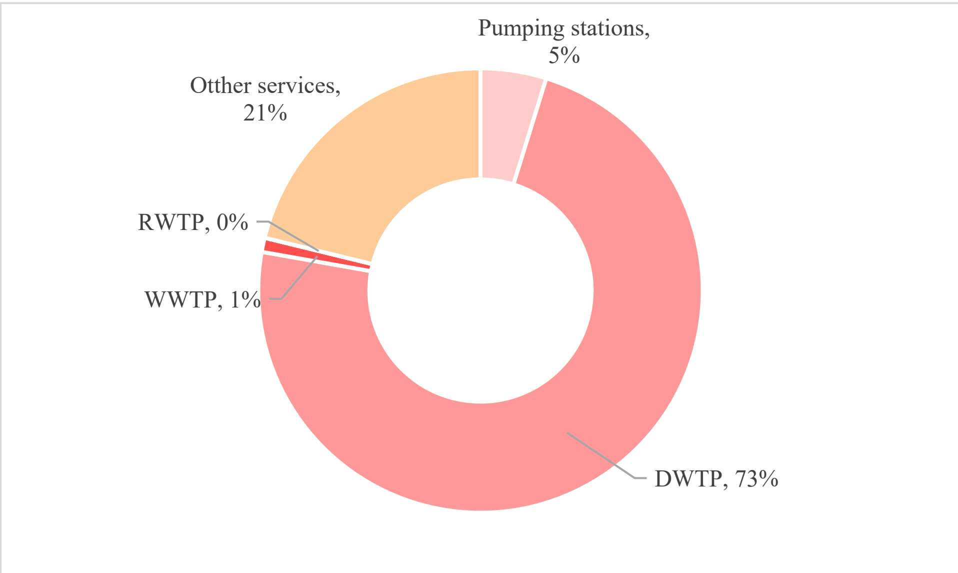

Figure 28. Average share of electricity consumption: elements in the urban water cycle and other services.

10 Evaluation with multi-criteria decision analysis

This chapter describes the multi-criteria decision analysis process that is performed to evaluate the 12 alternatives for the water-energy model. The evaluation process is performed to identify which alternative is optimal or the most sustainable. Therefore, several indicators are proposed to quantify and evaluate the characteristics from each alternative systematically.

The twelve optimized alternatives are evaluated under two different scenarios using multi-criteria decision analysis to determine which alternative is optimal. 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 [52]. In this case, the optimal alternative will be the one that gets the higher value. The additive model determines the value $v(a)$ of an alternative a as

$$v(a) = \sum_{r=1}^{m} w_r v_r(a_r) \tag{8}$$

where $w_r > 0$ and

$$\sum_{r=1}^{m} w_r = 1 \tag{9}$$

As stated above a_r indicates the value of the attribute X_r 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 [52].

10.1 Attributes' (indicators') description

In this study, the attributes (X) are the indicators. Three types of indicators are defined: performance, economic, and environmental (see Table 39). 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. Finally, the environmental indicator quantifies the GHG emissions from the energy system. The definition of each indicator and how their values are extracted from the model are described further in this section.

Table 39. Attributes (indicators) defined to evaluate the alternatives for the water-energy system.

No.	PERFORMANCE
	For Water:
1	Water shortage (m^3/month)
2	Percentage of time with water shortage (%)
3	Percentage of time with the water level from the water bodies below the set level (%)
4	Water treated but not reused (m^3/month)
	For Energy:
5	Renewable Energy production (MW/month)
6	Energy demand (MW/month)
7	Renewable energy shortage (MW/month)
8	Renewable energy rejected (MW/month)
9	Average daily RES penetration (%):
	ECONOMIC
10	Capital cost (M EUR)
11	O&M per year as a percentage of the capital cost (%)
	ENVIRONMENTAL
12	GHG emissions (10^3 kg CO_2-eq /year)

1. **Water shortage:** The water shortage is the sum of the irrigation water demand shortage and the inhabitant's water demand shortage. It is obtained by subtracting the amount of water supplied from the amount demanded. The hourly irrigation water demand is 0 when the hourly precipitation is higher than 1 mm/h (see section 5.1.7).
2. **Percentage of time with water shortage:** The time with water shortage is defined as the number of hours when the water shortage is greater than 0. Then, the percentage of time with water shortage is the time with water shortage divided by the total number of time steps executed by the model.
3. **Percentage of time with the water level from the water bodies below the set level:** It represents the percentage of time when the water level in the water bodies is below the set level.
4. **Water treated but not reused:** The amount of water treated but not reused is represented by the flows that are spilled by the treated wastewater storage tank (WWT), the irrigation and recovery water storage tank (IWT), and/or the rainwater storage tank (RWT).
5. **Renewable energy production:** Renewable energy production is the amount of electricity produced by wind turbines and/or PV panels. The electricity delivered by the battery is not considered renewable energy production.
6. **Energy demand:** The energy demand corresponds to the electricity demanded by the urban water cycle. For this research, the elements that contribute to the electricity demand are the water treatment facilities and the pumping stations.
7. **Renewable energy shortage:** The renewable energy shortage is defined as the electricity demand that is not supplied into the grid by electricity coming from the battery, wind turbines, and/or PV panels.
8. **Renewable energy rejected:** The renewable energy rejected is the amount of renewable energy produced by the wind turbines and/or PV panels that is not supplied to the grid and is not stored.
9. **Capital cost:** The capital cost is the total fixed expenses incurred to construct and purchase the different elements that integrate the water-energy system (see Chapter 7).
10. **O&M per year as a percentage of the capital cost:** The operation and maintenance (O&M) costs per year as a percentage of the capital cost are the total yearly expenses incurred to operate the different

elements from the water-energy system, without considering energy expenses, divided by the total capital cost.

11. **GHG emissions:** The GHG emissions are represented as Life Cycle CO_2-eq emissions. Their values are obtained from the literature. The GHG emissions are only considered for wind turbines, PV panels, and the battery. It is regarded as the Life Cycle Emissions because the technologies previously mentioned do not release greenhouse gases (GHG) during their operation.

10.2 Attributes' (indicators') weights

The weights (*w*) for each indicator are determined by using the swing method [52]. The decision-maker determines the weights in three (3) steps. The results for each step are shown in the different columns in Table 40:

1. Rank the indicators in order of relevance, where 1 is the most important.
2. Assign a score to each indicator
3. Normalize the weights to 1.

For step 1, it is given more preference to environmental aspects, such as RES penetration and treated water that is not reused, and less preference to economic aspects. It is observed in *column 1* that the most important attribute is the GHG emission, and the least is the percentage of time with the water level from the water bodies below the set level. In this research, the water shortage is not considered in the top 3 because the results demonstrate that the water shortage occurs in the irrigation system and not for the inhabitants' demand. In step 2, each attribute is scored on a scale that goes from 0 to 70. The scoring range can be defined by the decision-maker. This step is performed to specify the value differences between the different indicators. The different points are shown in *column 2.* Finally, in step 3, the attribute weights are determined by the normalization of the points (see *column 3)*. The purpose of normalization is to obtain one unique combination out of the set of many equivalent weight combinations [52]. The normalization process is performed as follows:

$$w_r = t_r / \sum_{i=1}^{m} t_i \tag{10}$$

Where w_r is the attribute weight and t_i the number of points per attribute.

Table 40. Weights for the indicators on performance, economic, and environmental aspects.

	Column:	*1*	*2*	*3*
No.	**PERFORMANCE**	**RANK**	**POINT**	**WEIGHTS**
	For Water:			
1	Water shortage (m^3/month)	7	45	0.082
2	Percentage of time with water shortage (%)	6	50	0.091
3	Percentage of time with the water level from the water bodies below the set level (%)	12	10	0.018
4	Water treated but not reused (m^3/month)	5	55	0.100
	For Energy:			
5	Renewable Energy production (MW/month)	11	15	0.027
6	Energy demand (MW/month)	8	40	0.073

7	Renewable energy shortage(MW/month)	3	65	0.118
8	Renewable energy rejected (MW/month)	4	60	0.109
9	Average daily RES penetration (%):	2	68	0.123
	ECONOMIC			
10	Capital cost (M EUR)	9	38	0.069
11	O&M per year as a percentage of the capital cost (%)	10	35	0.064
	ENVIRONMENTAL			
12	GHG emissions (10^3 kg CO_2-eq /year)	1	70	0.127

10.3 Attribute (indicator) value

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) yearly accumulated precipitation from the data set to see how each alternative performs under those conditions. The values obtained for each indicator, of each alternative, under the two scenarios are shown in Table 41 and Table 42.

Table 41. Attributes' (indicators') values for year 1992.

	SCENARIO YEAR 1992											
PERFORMANCE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
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%
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

Table 42. Attributes' (indicators') values for year 2015.

	SCENARIO YEAR 2015											
PERFORMANCE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
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

10.4 Value of the attribute (indicator) value function

The value function is a mathematical representation of the preference (p. 109) [52]. For each attribute *X,* the attribute value function $v_r(a_r)$ is defined as a linear function (see Table 43). For the indicators where a high value of the attribute a_r represents a negative outcome, for example, the water shortage, the attribute value function is:

$$v_r(a_r) = 1 - (a_r - a_{r,min})/(a_{r,max} - a_{r,min}) \tag{11}$$

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 values, 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:

$$v_r(a_r) = (a_r - a_{r,min})/(a_{r,max} - a_{r,min}) \tag{12}$$

The results obtained from the attribute value functions are shown in Table 44 and Table 45.

Table 43. Attribute value function for each indicator.

No.	PERFORMANCE	ATTRIBUTE VALUE FUNCTION
	For Water:	
1	Water shortage (m^3/month)	*Eq.* (11)
2	Percentage of time with water shortage (%)	*Eq.* (11)
3	Percentage of time with the water level from the water bodies below the set level (%)	*Eq.* (11)
4	Water treated but not reused (m^3/month)	*Eq.* (11)
	For Energy:	
5	Renewable Energy production (MW/month)	*Eq.* (12)
6	Energy demand (MW/month)	*Eq.* (11)
7	Renewable energy shortage(MW/month)	*Eq.* (11)
8	Renewable energy rejected (MW/month)	*Eq.* (11)
9	Average daily RES penetration (%):	*Eq.* (12)
	ECONOMIC	
10	Capital cost (M EUR)	*Eq.* (11)
11	O&M per year as a percentage of the capital cost (%)	*Eq.* (11)
	ENVIRONMENTAL	
12	GHG emissions (10^3 kg CO_2-eq /year)	*Eq.* (11)

Table 44. Values of the attribute value functions for the year 1992.

	SCENARIO YEAR 1992											
PERFORMANCE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
For Water:												
Water shortage	0.00	0.99	0.00	0.99	0.00	0.99	1.00	0.11	1.00	0.11	1.00	0.11
Percentage of time with water shortage	0.00	0.99	0.00	0.99	0.00	0.99	1.00	0.10	1.00	0.09	1.00	0.09
Percentage of time with the water level from the water bodies below the minimum level	0.00	1.00	0.00	1.00	0.00	1.00	1.00	0.00	1.00	0.00	1.00	0.00
Water treated but not reused	1.00	0.73	1.00	0.73	1.00	0.73	0.00	0.93	0.00	0.99	0.00	0.99
For Energy:												
Renewable Energy production	1.00	1.00	0.53	0.53	0.00	0.00	1.00	1.00	0.53	0.53	0.00	0.00
Energy demand	0.01	1.00	0.01	1.00	0.01	1.00	0.99	0.00	0.99	0.00	0.99	0.00
Renewable energy shortage	0.50	0.81	0.68	1.00	0.01	0.54	0.80	0.50	1.00	0.67	0.53	0.00
Renewable energy rejected	0.12	0.00	0.71	0.59	1.00	0.97	0.00	0.12	0.59	0.71	0.97	1.00
Average daily RES penetration	0.62	0.74	0.79	1.00	0.00	0.26	0.74	0.62	1.00	0.78	0.26	0.00
ECONOMIC												
Capital cost	0.18	0.20	0.57	0.59	0.98	1.00	0.01	0.00	0.39	0.40	0.81	0.81
O&M per year as a percentage of the capital cost	0.74	1.00	0.56	0.86	0.24	0.61	0.79	0.54	0.62	0.34	0.35	0.00
ENVIRONMENTAL												
GHG emissions	0.54	0.84	0.68	1.00	0.01	0.52	0.84	0.54	1.00	0.68	0.52	0.00

Table 45. Values of the attribute value functions for the year 2015.

	SCENARIO YEAR 2015											
PERFORMANCE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
For Water:												
Water shortage	0.00	1.00	0.00	1.00	0.00	1.00	1.00	0.00	1.00	0.00	1.00	0.00
Percentage of time with water shortage	0.00	1.00	0.00	1.00	0.00	1.00	1.00	0.00	1.00	0.00	1.00	0.00
Percentage of time with the water level from the water bodies below the minimum level	0.00	1.00	0.00	1.00	0.00	1.00	1.00	0.00	1.00	0.00	1.00	0.00
Water treated but not reused	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
For Energy:												
Renewable Energy production	1.00	1.00	0.53	0.53	0.00	0.00	1.00	1.00	0.53	0.53	0.00	0.00
Energy demand	0.00	1.00	0.00	1.00	0.00	1.00	1.00	0.00	1.00	0.00	1.00	0.00
Renewable energy shortage	0.45	0.77	0.67	1.00	0.00	0.53	0.77	0.45	1.00	0.67	0.53	0.00
Renewable energy rejected	0.13	0.00	0.70	0.58	1.00	0.96	0.00	0.13	0.58	0.70	0.96	1.00
Average daily RES penetration	0.57	0.70	0.78	1.00	0.00	0.28	0.70	0.57	1.00	0.78	0.28	0.00
ECONOMIC												
Capital cost	0.18	0.20	0.57	0.59	0.98	1.00	0.01	0.00	0.39	0.40	0.81	0.81
O&M per year as a percentage of the capital cost	0.74	1.00	0.56	0.86	0.24	0.61	0.79	0.54	0.62	0.34	0.35	0.00
ENVIRONMENTAL												
GHG emissions	0.51	0.82	0.67	1.00	0.00	0.51	0.82	0.51	1.00	0.67	0.51	0.00

10.5 Total value

The total value is obtained with Eq. (8). The results are obtained by multiplying the weights (Table 40) and multiplying them with the values of the attribute value function (Table 44 and Table 45). The total values are shown in Table 46, Table 47, and Figure 29.

Table 46. MCDA's total values for the year 1992.

	SCENARIO YEAR 1992											
PERFORMANCE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
For Water:												
Water shortage	0.00	0.08	0.00	0.08	0.00	0.08	0.08	0.01	0.08	0.01	0.08	0.01
Percentage of time with water shortage	0.00	0.09	0.00	0.09	0.00	0.09	0.09	0.01	0.09	0.01	0.09	0.01
Percentage of time with the water level from the water bodies below the minimum level	0.00	0.02	0.00	0.02	0.00	0.02	0.02	0.00	0.02	0.00	0.02	0.00
Water treated but not reused	0.10	0.07	0.10	0.07	0.10	0.07	0.00	0.09	0.00	0.10	0.00	0.10
For Energy:												
Renewable Energy production	0.03	0.03	0.01	0.01	0.00	0.00	0.03	0.03	0.01	0.01	0.00	0.00
Energy demand	0.00	0.07	0.00	0.07	0.00	0.07	0.07	0.00	0.07	0.00	0.07	0.00
Renewable energy shortage	0.06	0.10	0.08	0.12	0.00	0.06	0.09	0.06	0.12	0.08	0.06	0.00
Renewable energy rejected	0.01	0.00	0.08	0.06	0.11	0.11	0.00	0.01	0.06	0.08	0.11	0.11
Average daily RES penetration	0.08	0.09	0.10	0.12	0.00	0.03	0.09	0.08	0.12	0.10	0.03	0.00
ECONOMIC												
Capital cost	0.01	0.01	0.04	0.04	0.07	0.07	0.00	0.00	0.03	0.03	0.06	0.06
O&M per year as a percentage of the capital cost	0.05	0.06	0.04	0.05	0.02	0.04	0.05	0.03	0.04	0.02	0.02	0.00
ENVIRONMENTAL												
GHG emissions	0.07	0.11	0.09	0.13	0.00	0.07	0.11	0.07	0.13	0.09	0.07	0.00
TOTAL VALUE	***0.41***	***0.73***	***0.53***	***0.88***	***0.29***	***0.71***	***0.63***	***0.39***	***0.78***	***0.52***	***0.61***	***0.28***

Table 47. MCDA's total values for the year 2015.

	SCENARIO YEAR 2015											
PERFORMANCE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
For Water:												
Water shortage	0.00	0.08	0.00	0.08	0.00	0.08	0.08	0.00	0.08	0.00	0.08	0.00
Percentage of time with water shortage	0.00	0.09	0.00	0.09	0.00	0.09	0.09	0.00	0.09	0.00	0.09	0.00
Percentage of time with the water level from the water bodies below the minimum level	0.00	0.02	0.00	0.02	0.00	0.02	0.02	0.00	0.02	0.00	0.02	0.00
Water treated but not reused	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
For Energy:												
Renewable Energy production	0.03	0.03	0.01	0.01	0.00	0.00	0.03	0.03	0.01	0.01	0.00	0.00
Energy demand	0.00	0.07	0.00	0.07	0.00	0.07	0.07	0.00	0.07	0.00	0.07	0.00
Renewable energy shortage	0.05	0.09	0.08	0.12	0.00	0.06	0.09	0.05	0.12	0.08	0.06	0.00
Renewable energy rejected	0.01	0.00	0.08	0.06	0.11	0.10	0.00	0.01	0.06	0.08	0.10	0.11
Average daily RES penetration	0.07	0.09	0.10	0.12	0.00	0.03	0.09	0.07	0.12	0.10	0.03	0.00
ECONOMIC												
Capital cost	0.01	0.01	0.04	0.04	0.07	0.07	0.00	0.00	0.03	0.03	0.06	0.06
O&M per year as a percentage of the capital cost	0.05	0.06	0.04	0.05	0.02	0.04	0.05	0.03	0.04	0.02	0.02	0.00
ENVIRONMENTAL												
GHG emissions	0.06	0.10	0.09	0.13	0.00	0.07	0.10	0.06	0.13	0.09	0.07	0.00
TOTAL VALUE	***0.39***	***0.75***	***0.53***	***0.90***	***0.29***	***0.74***	***0.72***	***0.36***	***0.88***	***0.50***	***0.71***	***0.26***

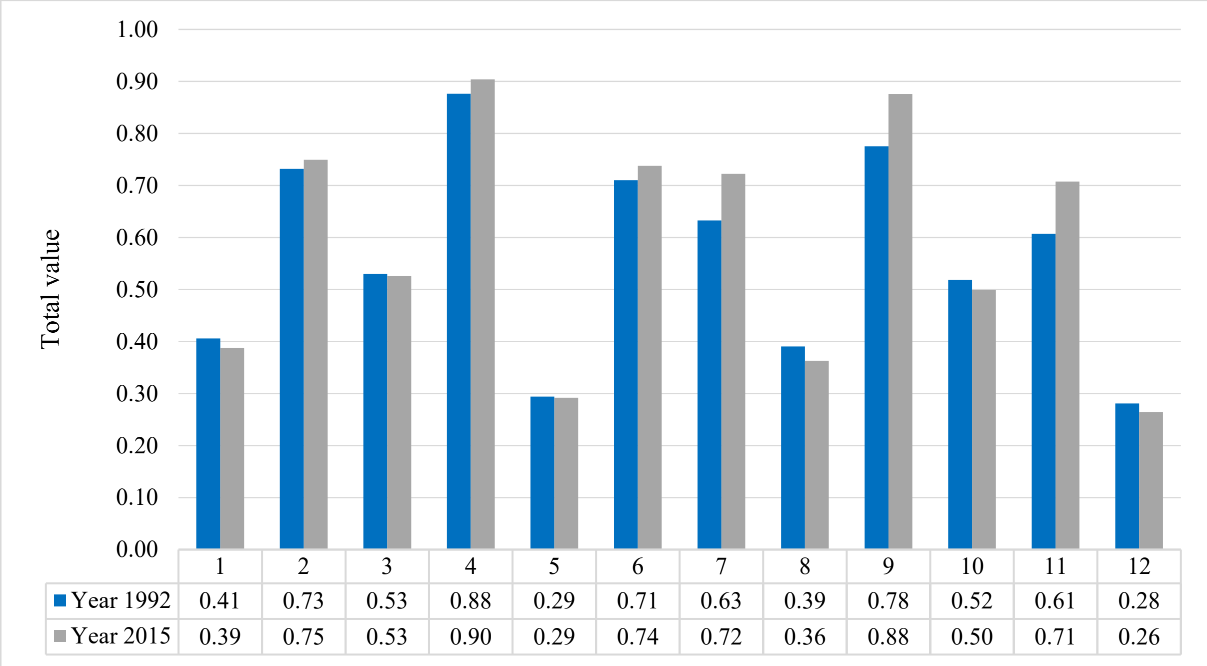

Figure 29. MCDA's total values for the years 1992 and 2015.

10.6 Sensitivity analysis

The sensitivity analysis is performed to evaluate how the results might change if the capital cost's weight (w_{10}) changes. The alternatives considered for this analysis are A1, A4, A5, A8, A9, and A12. The analysis is done only for the scenario with the maximum yearly accumulated precipitation (1992). The total value is calculated for every alternative when the capital cost's weight is 0 and when it is 1. Table 48 shows the weights for all the attributes when the capital cost's weight is 0 and 1. The changes in the weights are shown in Figure 30 and Figure 31.

Table 48. Attributes' (indicators') weights when w_{10} is 0 or 1.

No.	PERFORMANCE	$W_{10} = 0$	$W_{10} = 1$
	For Water:		
1	Water shortage (m^3/month)	0.088	0.000
2	Percentage of time with water shortage (%)	0.097	0.000
3	Percentage of time with the water level from the water bodies below the set level (%)	0.019	0.000
4	Water treated but not reused (m^3/month)	0.107	0.000
	For Energy:		
5	Renewable Energy production (MW/month)	0.029	0.000
6	Energy demand (MW/month)	0.078	0.000
7	Renewable energy shortage(MW/month)	0.127	0.000
8	Renewable energy rejected (MW/month)	0.117	0.000
9	Average daily RES penetration (%):	0.133	0.000
	ECONOMIC		
10	Capital cost (M EUR)	**0.000**	**1.000**
11	O&M per year as a percentage of the capital cost (%)	0.068	0.000
	ENVIRONMENTAL		
12	GHG emissions (10^3 kg CO_2-eq /year)	0.136	0.000

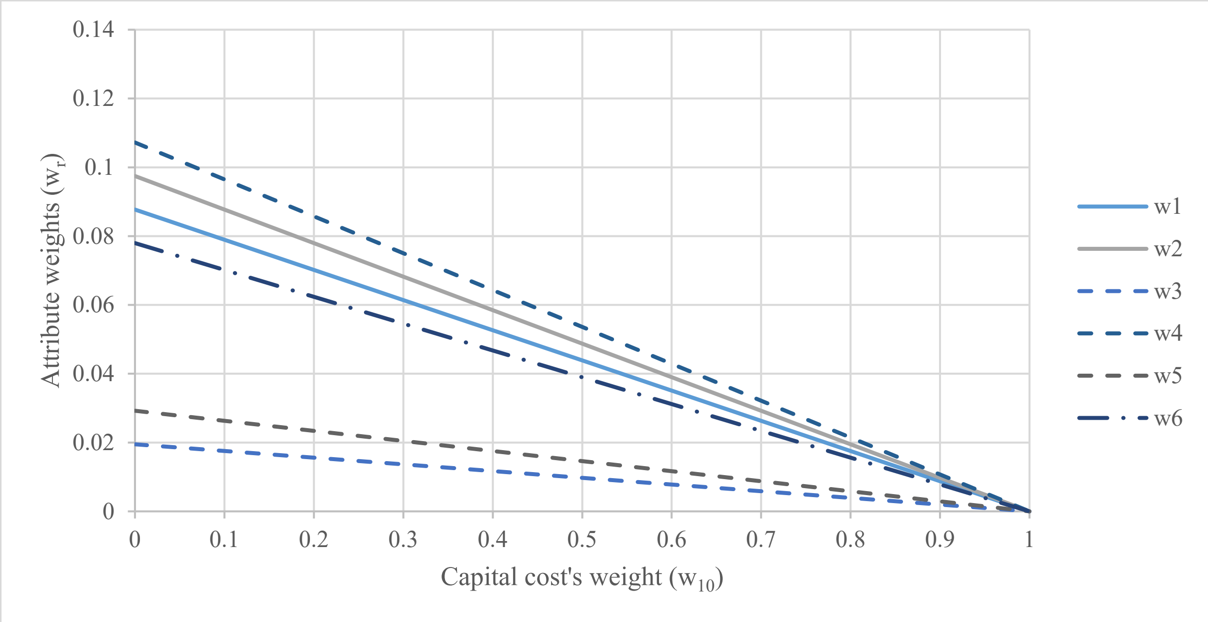

Figure 30. Sensitivity analysis for the weights w_1 to w_6.

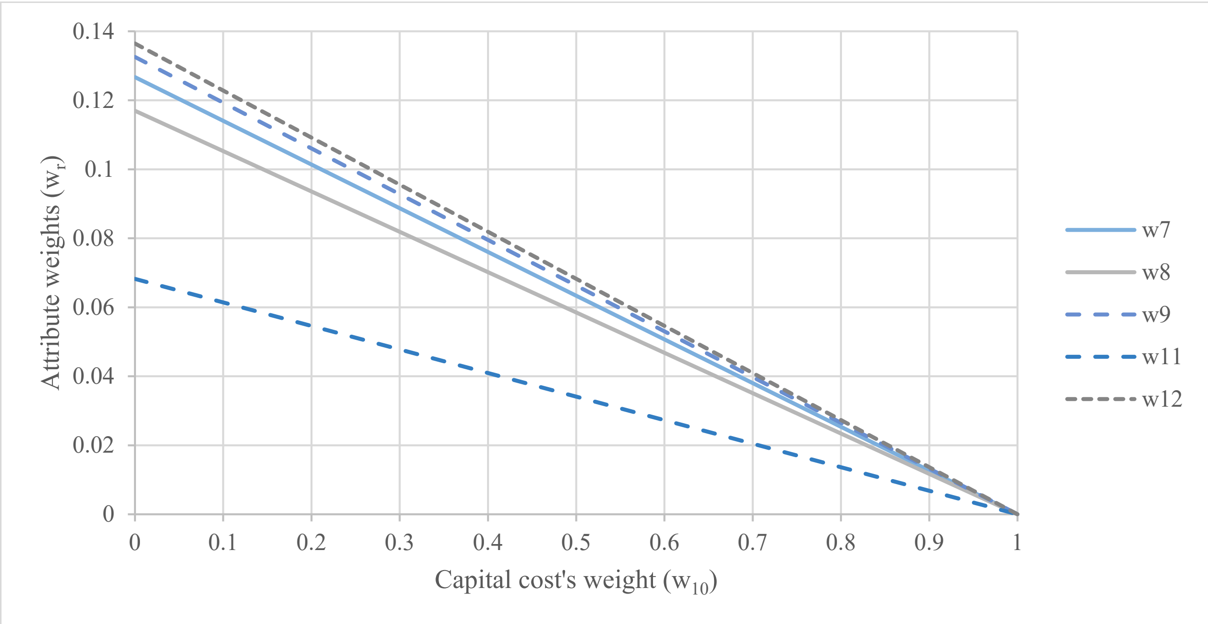

Figure 31. Sensitivity analysis for the weights w_7 to w_{12}.

The total values for each alternative when the capital cost's weight (w_{10}) is 0 are shown in Table 49. The total values for each alternative when the capital cost's weight (w_{10}) is 1 are shown in Table 50. Figure 32 shows the changes in the total score for each alternative compared to the changes in w_{10}.

Table 49. MCDA's total values when w_{10} is 0 for the year 1992.

SCENARIO YEAR 1992 (CAPITAL'S WEIGHT IS 0)												
PERFORMANCE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
For Water:												
Water shortage	0.00	0.09	0.00	0.09	0.00	0.09	0.09	0.01	0.09	0.01	0.09	0.01
Percentage of time with water shortage	0.00	0.10	0.00	0.10	0.00	0.10	0.10	0.01	0.10	0.01	0.10	0.01
Percentage of time with the water level from the water bodies below the minimum level	0.00	0.02	0.00	0.02	0.00	0.02	0.02	0.00	0.02	0.00	0.02	0.00
Water treated but not reused	0.11	0.08	0.11	0.08	0.11	0.08	0.00	0.10	0.00	0.11	0.00	0.11
For Energy:												
Renewable Energy production	0.03	0.03	0.02	0.02	0.00	0.00	0.03	0.03	0.02	0.02	0.00	0.00
Energy demand	0.00	0.08	0.00	0.08	0.00	0.08	0.08	0.00	0.08	0.00	0.08	0.00
Renewable energy shortage	0.06	0.10	0.09	0.13	0.00	0.07	0.10	0.06	0.13	0.09	0.07	0.00
Renewable energy rejected	0.01	0.00	0.08	0.07	0.12	0.11	0.00	0.01	0.07	0.08	0.11	0.12
Average daily RES penetration	0.08	0.10	0.10	0.13	0.00	0.03	0.10	0.08	0.13	0.10	0.03	0.00
ECONOMIC												
Capital cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O&M per year as a percentage of the capital cost	0.05	0.07	0.04	0.06	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.00
ENVIRONMENTAL												
GHG emissions	0.07	0.11	0.09	0.14	0.00	0.07	0.11	0.07	0.14	0.09	0.07	0.00
TOTAL VALUE	***0.42***	***0.77***	***0.53***	***0.90***	***0.24***	***0.69***	***0.68***	***0.42***	***0.80***	***0.53***	***0.59***	***0.24***

Table 50. MCDA's total values when w_{10} is 1 for the year 1992.

	SCENARIO YEAR 1992 (CAPITAL'S WEIGHT IS 1)											
PERFORMANCE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
For Water:												
Water shortage	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Percentage of time with water shortage	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Percentage of time with the water level from the water bodies below the minimum level	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water treated but not reused	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
For Energy:												
Renewable Energy production	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy demand	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Renewable energy shortage	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Renewable energy rejected	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average daily RES penetration	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ECONOMIC												
Capital cost	0.18	0.20	0.57	0.59	0.98	1.00	0.01	0.00	0.39	0.40	0.81	0.81
O&M per year as a percentage of the capital cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ENVIRONMENTAL												
GHG emissions	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL VALUE	***0.18***	***0.20***	***0.57***	***0.59***	***0.98***	***1.00***	***0.01***	***0.00***	***0.39***	***0.40***	***0.81***	***0.81***

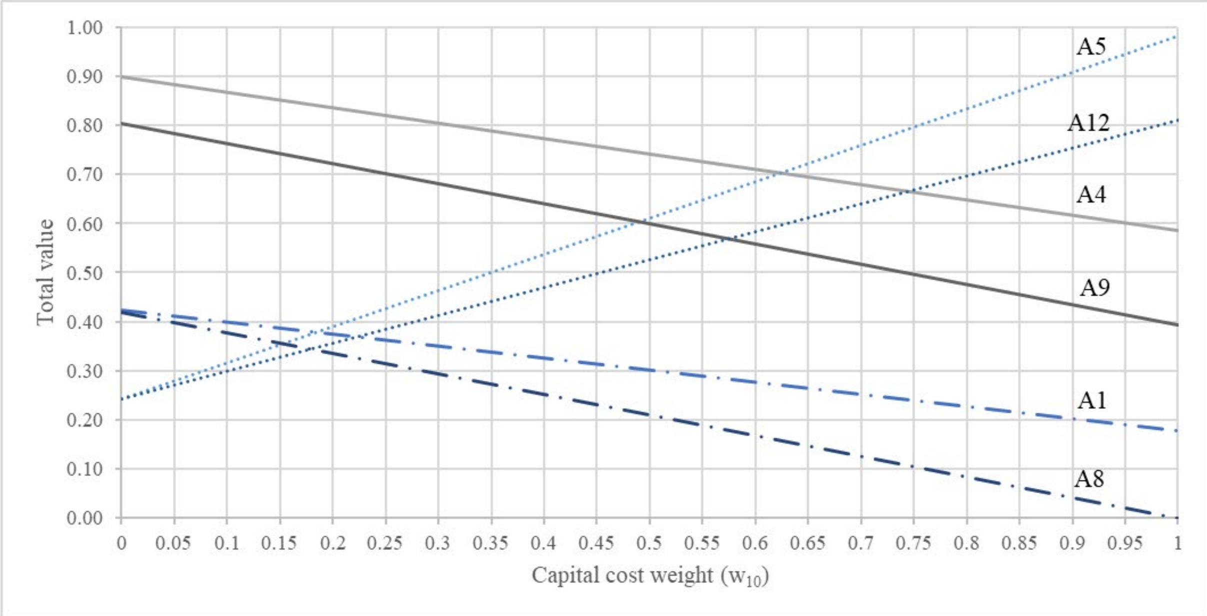

Figure 32. Total values when the capital cost weight (w_{10}) changes from 0 to 1.

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Appendix I : Overview of H2RES model

H2RES is a computer model designed to simulate the integration of renewable energy sources (RES) into island energy systems [24]. It is primarily used to balance the water, electricity, hydrogen demand, and determine appropriate energy storage and supply [16]. A model like this is required to simulate the energy systems for this research. However, it is restricted for internal use by their developers which are the Instituto Técnico Superior and the University of Zaberg [23]. Nevertheless, most of its theoretical background can be found in the literature [6], [7], [16], [24], [53]. Therefore, it is possible to build a similar model by using the theoretical basis from H2RES.

The purpose of this Appendix is to show the structure, energy balance equations, and constraints from the model H2RES so they can serve as foundations to build a new model. The information related to H2RES will be consulted from existing literature and then organized. In that way, in this Appendix, section 1 shows the main structure of H2RES. Section 2 contains the energy balance equations. Section 4 shows the main constraints that are considered in some projects modeled by H2RES.

Section 1. H2RES modules

This section describes the modules that integrate the structure of the model H2RES. This model uses different modules and the most relevant for this research are the wind, solar, and load modules. All the modules use basic technical data of equipment and hourly meteorological data from intermittent sources [16].

Wind module:

The wind module uses the wind velocity data at 10 m height and then adjusts them to the wind turbines hub's height. Then, it converts the velocities to the total potential wind output [7], [24], [53]. The adjustment can be done using the equation [6]:

$$v_z = v_{10}\left(\frac{z}{10}\right)^{0.14}$$

Where:

v_z – Wind velocity at height "z"

v_{10} – Wind velocity at 10 m

z – height

Solar module:

The solar module works with the total solar radiation obtained from meteorological stations or available models, for a given latitude [6]. Then, the total horizontal radiation is adjusted for the inclination of the photovoltaics (PV) array, and finally to electrical potential output [7], [8], [24]. The efficiency data for the PV, modules, inverter, line losses, and other components, can be obtained from the manufacturers.

Load module:

The load module will make a balance between the energy demand and supply. The hourly load of power of the system has to be obtained from the local utility and this data is usually represented by the load duration curves (LDC) [6], [7]. The LCD is a "plot of the system load demand in descending order over a certain period" (p.397) [54]. It "expresses the relation between time and demand, showing the percent of the time where the demand is greater or equal to a certain level" (p.29) [55].

Nevertheless, the LCD cannot be used well with intermittent RES (i.e. wind and solar energy) when they represent a significant part of the system, which is the case for small islands. The RES will provide an energy output on an hourly basis that will be between 0 and maximum installed, which can be higher than the total load. Therefore, the amount of renewable energy taken by the system can only be calculated by comparing the demand and supply on an hourly basis [6], [7]. Load modules can be based on maximum acceptable renewable electricity or a 100% renewable electricity penetration. The excess of energy is available for storage, desalination, or other kinds of non-time-dependent services [6], [8], [53].

Storage module:

The storage module can be based either on an electrolyzer, storing the energy as hydrogen, or storing electricity in a battery. The input into the storage system is restrained by the storage equipment characteristics. For example, the power and charging capacity of the electrolyzers and/or batteries. Therefore, the surplus renewable energy that cannot be taken by the storage systems must be rejected or employed on non-time-dependent services [6], [24]. Contrary to that, if there is still an unsatisfied electricity load, it is covered by fossil fuel blocks or by the mainland grid [53].

H2RES works with certain storage efficiency, which is around 50-60% for electrolyzer, and 90% for batteries. In addition, it is expected that the electrolyzer already produces hydrogen with enough pressure suitable for storing it and avoiding the need for compression. The storage vessel and the electrolyzer output pressure are the parameters that limit the storage capacity [6]. Finally, the stored hydrogen can be retrieved at any moment and be used for transportation or to produce electricity using a fuel cell. For the last, the efficiency is considered around 50%. A small fuel cell can be controlled by the grid. Nevertheless, a bigger fuel cell must have frequency and voltage control.

Hydrogen storage:

According to Duic et al. [7], to fairly asses the hydrogen economy of the system, it is necessary to design de system in such a way that the hydrogen stock at the beginning of the year is similar to the one at the end of the year.

The energy accumulated in hydrogen storage in hour *n* is:

$$E_{H_2}^{n} = E_{H_2}^{n-1} - \frac{E_{FC}}{\mu_{FC}} - E_{H_2load} + \mu_{el} \cdot E_{el}$$

Where:

$E_{H_2}^{n} = energy\ accumulated\ in\ hydrogen\ storage\ in\ hour\ "n"$

$E_{H_2}^{n-1} = energy\ accumulated\ in\ hydrogen\ storage\ in\ hour\ "n-1"$

$E_{FC} =\ energy\ output\ from\ fuel\ cells$

$\mu_{FC} = fuel\ cell\ efficiency\ (around\ 50\%)$

$E_{H_2load} = energy\ output\ from\ hydrogen\ storage$

$\mu_{el} = electrolyzer\ efficiency\ (around\ 50-60\%)$

$E_{el} =\ energy\ consumed\ by\ electrolysing\ water$

With the expression presented above, it is guaranteed that the hydrogen stored is going to be in the range between empty and full. Furthermore, the fuel cell will not be allowed to work in case the hydrogen storage stores less hydrogen than the required to supply hydrogen load for a set number of hours t_{H_2sec}:

$$E_{H_2}^{n-1} < \ t_{H_2sec} \cdot E_{H_2load} \ \rightarrow \ E_{FC} = 0$$

Where:

$E_{H_2}^{n-1} = energy\ accumulated\ in\ hydrogen\ storage\ in\ hour\ "n-1"$

$t_{H_2sec} = number\ of\ hours\ that\ must\ be\ secured\ for\ supply$

$E_{H_2load} = energy\ output\ from\ hydrogen\ storage$

$$E_{FC} = \ energy\ output\ from\ fuel\ cells$$

Section 2. Energy balance equations

This section describes the energy balancing equations that support the computer model H2RES. All the equations were retrieved from Duic et al. [7].

The demand is supplied as follow:

$$E_{load} = E_{I,t} + E_T + E_{FC} + E_{bat,out} - E_P - E_{el} - E_{bat,in} + E_D$$

Where:

$$E_{load} = energy\ demand$$

$$E_{I,t} = energy\ output\ from\ intermittent\ renewable\ energies$$

$$E_T = energy\ output\ from\ hydro\ turbines$$

$$E_{FC} = \ energy\ output\ from\ fuel\ cells$$

$$E_{bat,out} = energy\ output\ from\ batteries$$

$$E_P = \ energy\ consumed\ by\ pumping\ water$$

$$E_{el} = \ energy\ consumed\ by\ electrolysing\ water$$

$$E_{bat,in} = \ energy\ consumed\ by\ charging\ batteries$$

$$E_D = \ energy\ output\ from\ diesel\ blocks\ in\ use\ at\ that\ moment$$

The intermittent renewable energy that is taken by the system ($E_{I,t}$) is defined by the maximum percentage of hourly renewable energy that can be taken by the grid (φ_I), and the intermittent potential ($E_{I,pot}$):

$$E_{I,t} = Min\ (\varphi_I E_{load}, E_{I,pot})$$

Where:

$$E_{I,t} = \ energy\ output\ from\ intermittent\ renewable\ energies$$

$$\varphi_I = \ maximum\ percentage\ of\ renewable\ energy\ that\ can\ enter\ the\ grid$$

$$E_{load} = energy\ demand$$

$$E_{I,pot} = intermittent\ energy\ potential$$

Where intermittent potential is a sum of wind and solar PV potentials:

$$E_{I,pot} = E_{W,pot} + E_{PV,pot}$$

Where:

$$E_{W,pot} = energy\ output\ from\ wind\ turbines$$

$$E_{PV,pot} = energy\ output\ from\ PV\ panels$$

The total intermittent potential ($E_{I,pot}$) will be either taken by the system or used in pumps, by electrolyser, or stored in batteries, and the rest will be rejected:

$$E_{I,pot} = E_{I,t} + E_P + E_{el} + E_{bat,in} + E_r$$

Where:

$E_{I,pot} = intermittent\ energy\ potential$

$E_{I,t} = energy\ output\ from\ intermittent\ renewable\ energies$

$E_P = energy\ consumed\ by\ pumping\ water$

$E_{el} = energy\ consumed\ by\ electrolysing\ water$

$E_{bat,in} = energy\ consumed\ by\ charging\ batteries$

$E_r = energy\ rejected\ by\ the\ system$

Section 3. Constraints

RES penetration:

The percentage of renewable energy that can be taken by the energy grid depend on the existence of frequency controllers. For energy sources that doesn´t have frequency control, the allowed RES penetration is around 30%. That percentage can be higher only for short periods of time. This limitations, will typically for wind, allows 10-15% penetration of wind energy on the total yearly electricity produced [6]. When there is frequency and voltage control, it is possible to allow a 100% penetration of renewable energies. Nevertheless, sometimes due to the wind quality and its intermittent quality it is not possible to reach 100% penetration.

Optimization:

For the analysis of the island of Mljet presented by Krajacic et al. [16], the scenarios with 30% penetration limit are optimized to keep the rejected renewable energy below or very close to 10%. While the scenarios that allow 100% penetration are optimized to keep the exported electricity at 30% of yearly intermittent potential. In addition, the installed components are kept as small as possible.

Sequence of sources:

The sequence of sources in the supplying and demand must be set up according to the designer criteria. According to Krajacic et al. [53] in most of the cases, the system will use firstly the geothermal energy, then biomass, and lastly the rest of renewables.

Appendix II : Water demand calculation

Table 51. Population water demand (source: GFA Grupo Inmobiliario SC, personal communication, December 9, 2021).

	Area	Quantity	Units	Guests per room	Guests per unit	No. Inhab.	Type of inhabitant	Water consumption (l/inhab/day)	Water demand (m^3/d)
ESTATE LOTS	**ESTATE LOTS**					**1,380**			**828.00**
	TYPICAL VILLAS	**116**	**units**			**1,380**			**828.00**
	Five Bedroom Villa	36	units	2.0	10	360	Resident	600	216.00
	Six Bedrooms Villa	50	units	2.0	12	600	Resident	600	360.00
	Seven Bedroom Villa	30	units	2.0	14	420	Resident	600	252.00
RESORT	**RESORT**					**1,029**			**418.15**
	STANDARD ROOMS	**37**	**keys**			**194**			**194.00**
	STANDARD ROOM	10	keys	3.0	6	60	Guest	1,000	60.00
	TWO STORY STANDARD	8	keys	3.0	6	48	Guest	1,000	48.00
	EXECUTIVE VILLA	5	keys	2.0	4	20	Guest	1,000	20.00
	ONE BEDROOM SUITE	10	keys	2.0	4	40	Guest	1,000	40.00
	TWO BEDROOM SUITE	1	keys	3.0	6	6	Guest	1,000	6.00
	PRESIDENTIAL SUITE	1	keys	2.0	8	8	Guest	1,000	8.00
	OVERLAND SUITE	2	keys	3.0	6	12	Guest	1,000	12.00
	OVERWATER	**17**	**keys**			**38**			**38.00**
	STANDARD	14	keys	2.0	2	28	Guest	1,000	28.00
	ESTÁNDAR WITH LOCK OFF	1	keys	2.0	4	4	Guest	1,000	4.00
	ONE BEDROOM SUITE	1	keys	2.0	2	2	Guest	1,000	2.00
	TWO BEDROOM SUITE	1	keys	2.0	4	4	Guest	1,000	4.00
	BRANDED RESIDENTIAL	**24**	**units**			**144**			**144.00**
	Two Bedroom	6	units	2.0	4	24	Guest	1,000	24.00
	Three Bedroom	12	units	2.0	6	72	Guest	1,000	72.00
	Four Bedroom	6	units	2.0	8	48	Guest	1,000	48.00
	PUBLIC AREAS	**3611**	**m2**			**635**			**39.75**
	Lobby @ Main Building	29	m2		4	4	Visitant	50	0.20
	FamilyClub	427	m2		100	100	Visitant	50	5.00
	Pools restrooms	47	m2		8	8	Visitant	50	0.40
	Lawn Area	33	m2		8	8	Visitant	50	0.40
	Meal restaurant/pool side bar	457	m2		100	100	Visitant	50	5.00
	Main Kitchen	550	m2		30	30	Worker	150	4.50
	Staff Dinning	188	m2		100	100	Visitant	50	5.00
	Adult Pool Bar and grill	273	m2		50	50	Worker	150	7.50
	Service bar+storage MEP offices	44	m2		8	8	Visitant	50	0.40

	Kids for all Seasons	44	m2		25	25	Visitant	50	1.25
	Specialty Restaurant	198	m2		100	100	Visitant	50	5.00
	Spa	1222	m2		100	100	Visitant	50	5.00
	Retail	100	m2		2	2	Visitant	50	0.10
	BOH					**18**			**2.40**
	Housekeeping stations guestrooms	5	units		5	5	Worker	150	0.75
	Housekeeping stations residences	1	units		10	10	Worker	150	1.50
	Front Office	80	m2		3	3	Visitant	50	0.15
MARINA	**MARINA**					**462**			**79.30**
	BRANDED RESIDENTIAL	**13**	**units**			**106**			**59.10**
	Four Bedroom	12	units	2.0	8	96	Resident	600	57.60
	Housekeeping stations residences	1	units		10	10	Worker	150	1.50
	PUBLIC AREAS	**1011**	**m2**			**139**			**8.85**
	Marina reception Pavilion	203	m2		20	20	Visitant	50	1.00
	Resort Main Building Lobby	65	m2		4	4	Visitant	50	0.20
	Front Office	14	m2		3	3	Worker	150	0.45
	Beach Club		m2		8	8	Visitant	50	0.40
	Park		m2		6	6	Visitant	50	0.30
	Retail	100	m2		2	2	Visitant	50	0.10
	Fitness	260	m2		5	5	Visitant	50	0.25
	Event facilities-funtion rooms		m2		35	35	Visitant	50	1.75
	Event facilities-Ballroom and outdoor event space		m2		20	20	Visitant	50	1.00
	Event and meeting room		m2		4	4	Worker	150	0.60
	Banquet Kitchen		m2		8	8	Worker	150	1.20
	Nat Geo	300	m2		10	10	Visitant	50	0.50
	Dive Centre Marine Discovery Centre, Sports	337	m2		10	10	Visitant	50	0.50
	Security & Loading Dock		m2		4	4	Worker	150	0.60
	F&B OUTLETS	**409**	**m2**			**217**			**11.35**
	General Store & Bakery	64	m2		12	12	Visitant	50	0.60
	Bar & Lounge	50	m2		65	65	Visitant	50	3.25
	Bar & Lounge PANTRY		m2		5	5	Worker	150	0.75
	Bar/ Lobby Lounge /Coffee Bar (40s interior)	80	m2		40	40	Visitant	50	2.00
	Young Adults	185	m2		35	35	Visitant	50	1.75
	Golf Bar & Grill (10s interior + 50s exterior)	30	m2		60	60	Visitant	50	3.00
BOH BUILDINGS	**BOH BUILDINGS**					**131**			**37.65**
	GENERAL	**7234**	**m2**	**-**		**131**			**37.65**
	Administration	1541	m2		30	30	Worker	150	4.50
	Finance	629	m2		6	6	Worker	150	0.90

	Security	447	m2		10	10	Worker	150	1.50
	Human Facilities	707	m2		15	15	Worker	150	2.25
	Staf Housein (On-Island)	3064	m2		40	40	Resident	600	24.00
	Houskeeping	286	m2		10	10	Worker	150	1.50
	Laundry	350	m2		10	10	Worker	150	1.50
	Food Service + Loading Docks	210	m2		10	10	Worker	150	1.50
GOLF	**GOLF**					**311**			**34.65**
	PUBLIC AREAS	**576**	**m2**	**-**		**147**			**10.05**
	Golf Clubhouse	290	m2		15	15	Visitant	50	0.75
	Restaurant	50	m2		50	50	Visitant	50	2.50
	2 Confort Station + restaurant		m2		50	50	Visitant	50	2.50
	Administration offices+trabajadores	45	m2		15	15	Worker	150	2.25
	Maintenance golf	45	m2		5	5	Worker	150	0.75
	Farm		m2		7	7	Worker	150	1.05
	Pro Shop /Retail	146	m2		5	5	Visitant	50	0.25
	STAFF HOUSING	**154**	**units**	**-**		**164**			**24.60**
	Management Compound	5	units	1	5	5	Worker	150	0.75
	Non Management	64	units	1	64	64	Worker	150	9.60
	Temporary Facilities	72	units	1	72	72	Worker	150	10.80
	Administration	5	units	1	5	5	Worker	150	0.75
	Doctor’s Office	8	units	1	8	8	Worker	150	1.20
	Maintenance				10	10	Worker	150	1.50
					TOTAL	*3,313*			*1,397.75*
					The population’s daily water demand is			***1,397.75***	*m^3/d*

Table 52. Pool’s water demand (source: GFA Grupo Inmobiliario SC, personal communication, December 9, 2021).

Paremeter	**Value**	**Units**
POOLS		
Evaporation rate	0.008	m/d
Pools’ area (hotel)	1979.16	m2
Water demand for evaporation	15.83	m3/d

The pools’ daily water demand due to evaporation is ***15.83*** *m^3/d*

Table 53. Irrigation water demand (source: GFA Grupo Inmobiliario SC, personal communication, December 9, 2021).

Paremeter	**Value**	**Units**
IRRIGATION		
Golf field irrigation	2,148.00	m3/d
Additional irrigation	185.00	m3/d
TOTAL	2,333.00	m3/d

The irrigation system daily water demand is ***2,333.00*** *m^3/d*

Appendix III : Monthly water patterns calculation for inhabitants' water demand

Table 54. Belize's total tourist arrivals per year[34–36] .

Total Tourist Arrivals	2012	2013	2014	2015	2016	2017	2018	2019	2020
January	23,273	26,393	29,062	28,589	35,593	35,742	46,353	47,923	45,691
February	24,331	26,915	30,265	29,897	35,419	37,026	43,485	47,647	48,525
March	33,321	33,698	36,682	36,804	40,378	41,899	52,321	55,000	22,774
April	22,282	21,557	26,480	25,258	28,454	35,649	38,165	43,707	584
May	20,014	20,704	23,847	22,133	26,884	29,471	33,769	33,988	414
June	23,107	24,733	26,461	27,059	31,928	35,110	41,154	40,153	102
July	23,880	25,450	27,333	27,782	33,392	35,839	43,773	41,606	514
August	17,559	18,793	20,013	20,908	23,194	27,340	31,732	30,822	561
September	9,920	9,133	9,971	12,061	15,773	16,684	18,953	17,635	644
October	12,374	13,219	13,613	16,920	19,116	21,102	22,456	22,495	2,963
November	19,517	20,839	20,429	27,052	26,884	34,312	35,833	36,221	4,583
December	28,340	28,926	29,926	36,231	37,230	46,805	50,769	51,331	8,907
Total	257,918	270,360	294,082	310,694	354,245	396,979	458,763	468,528	136,262
Mean	21,493	22,530	24,507	25,891	29,520	33,082	38,230	39,044	11,355

Table 55. Relation between the Belize's total tourist arrivals and the yearly mean.

Total Tourist Arrivals / Yearly Mean Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	Mean without 2020 (Monthly peak factor)
January	1.083	1.171	1.186	1.104	1.206	1.080	1.212	1.227	4.024	1.159
February	1.132	1.195	1.235	1.155	1.200	1.119	1.137	1.220	4.273	1.174
March	1.550	1.496	1.497	1.421	1.368	1.267	1.369	1.409	2.006	1.422
April	1.037	0.957	1.081	0.976	0.964	1.078	0.998	1.119	0.051	1.026
May	0.931	0.919	0.973	0.855	0.911	0.891	0.883	0.871	0.036	0.904
June	1.075	1.098	1.080	1.045	1.082	1.061	1.076	1.028	0.009	1.068
July	1.111	1.130	1.115	1.073	1.131	1.083	1.145	1.066	0.045	1.107
August	0.817	0.834	0.817	0.808	0.786	0.826	0.830	0.789	0.049	0.813
September	0.462	0.405	0.407	0.466	0.534	0.504	0.496	0.452	0.057	0.466
October	0.576	0.587	0.555	0.654	0.648	0.638	0.587	0.576	0.261	0.603
November	0.908	0.925	0.834	1.045	0.911	1.037	0.937	0.928	0.404	0.941
December	1.319	1.284	1.221	1.399	1.261	1.415	1.328	1.315	0.784	1.318

NOTE: *The year 2020 is not considered in the calculations because it shows atypical values.*

Appendix IV : Multi-objective optimization figures

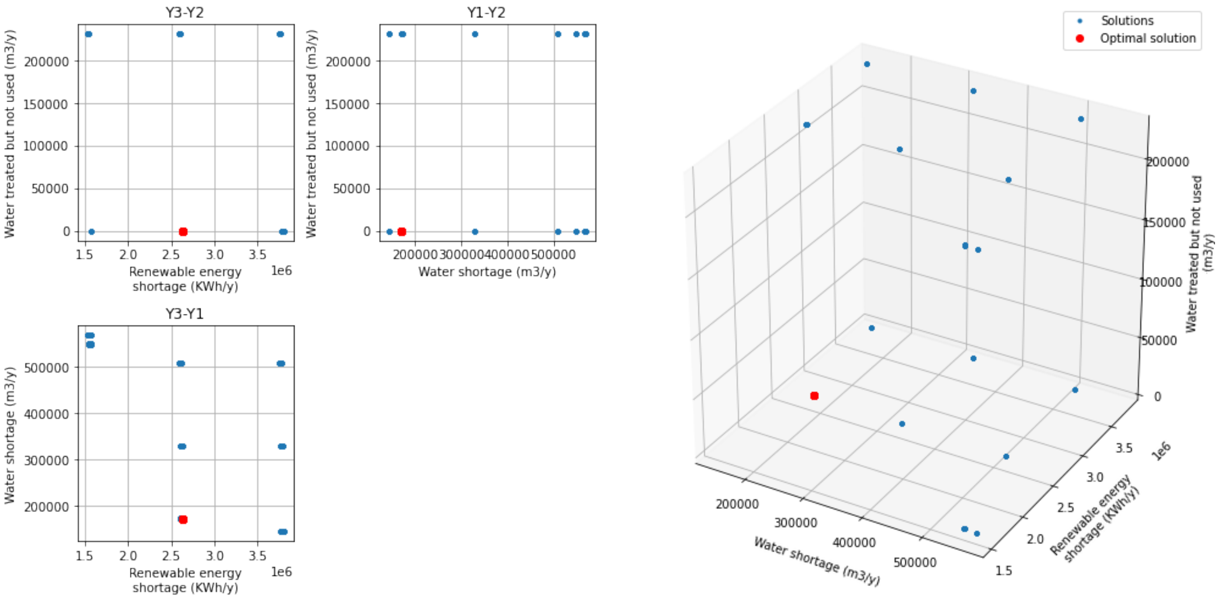

Figure 33. Multi-objective optimization results: Alternative 1.

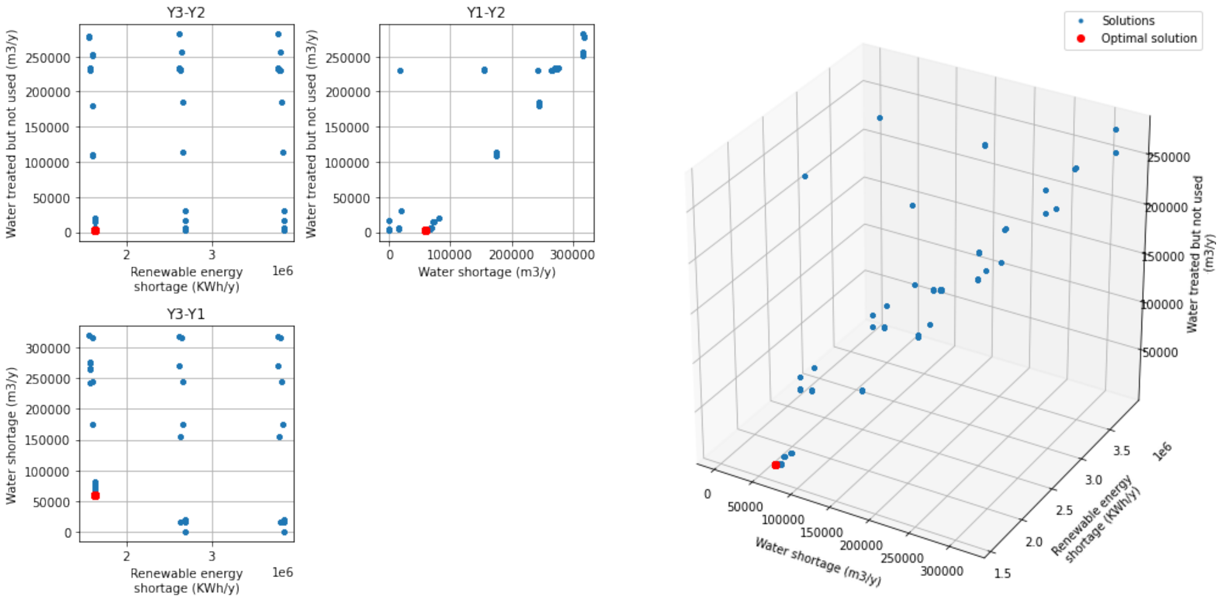

Figure 34. Multi-objective optimization results: Alternative 2.

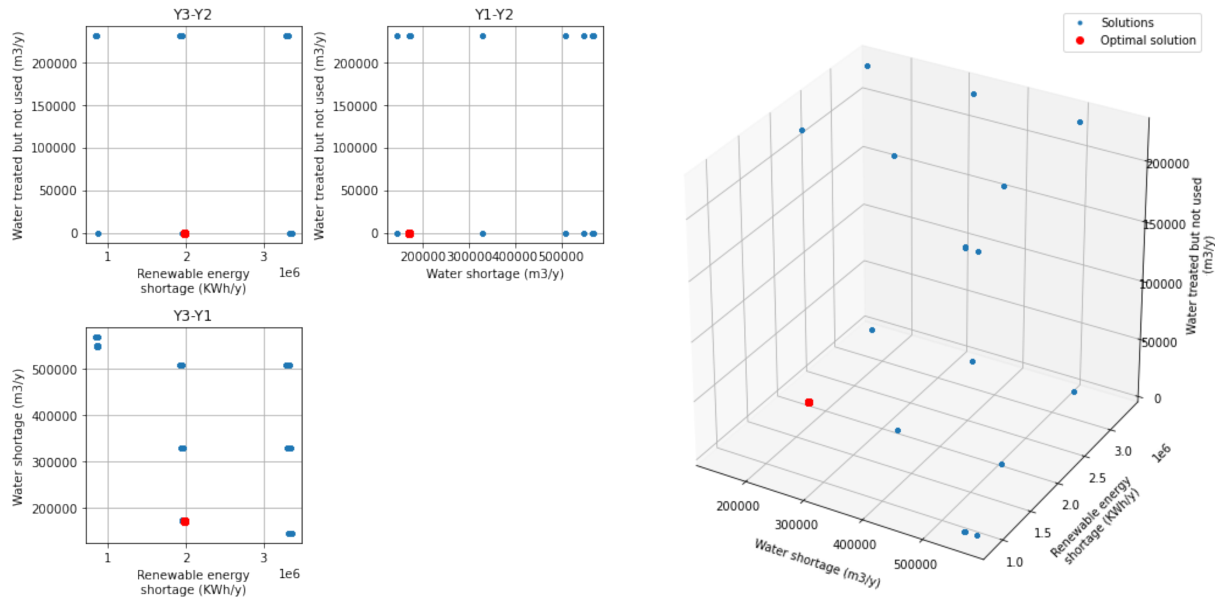

Figure 35. Multi-objective optimization results: Alternative 3.

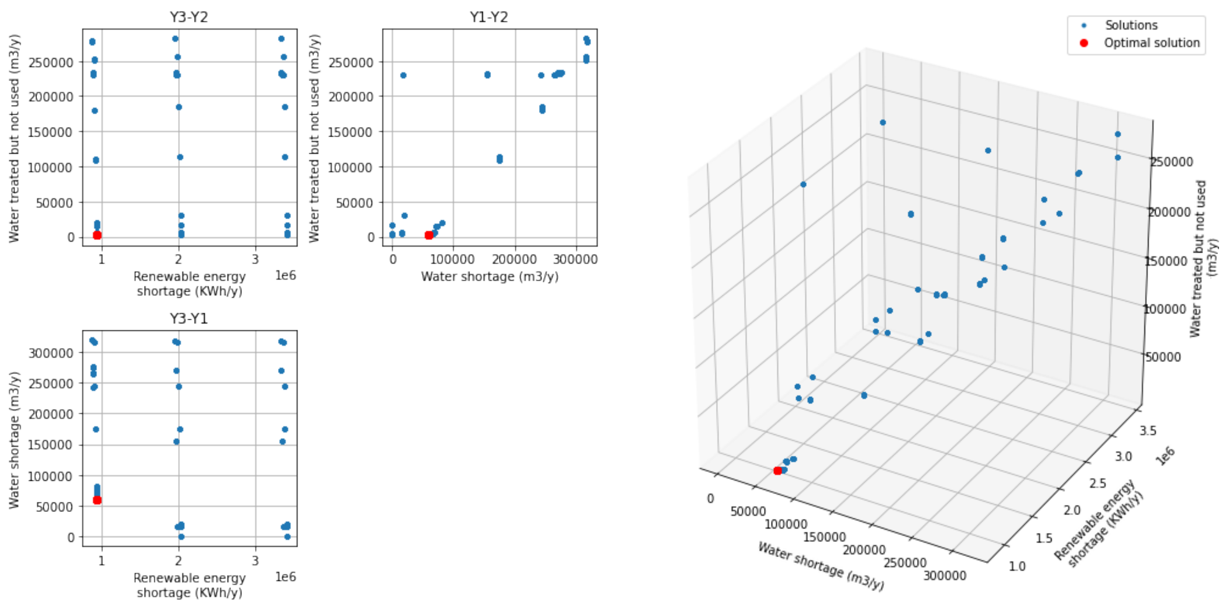

Figure 36. Multi-objective optimization results: Alternative 4.

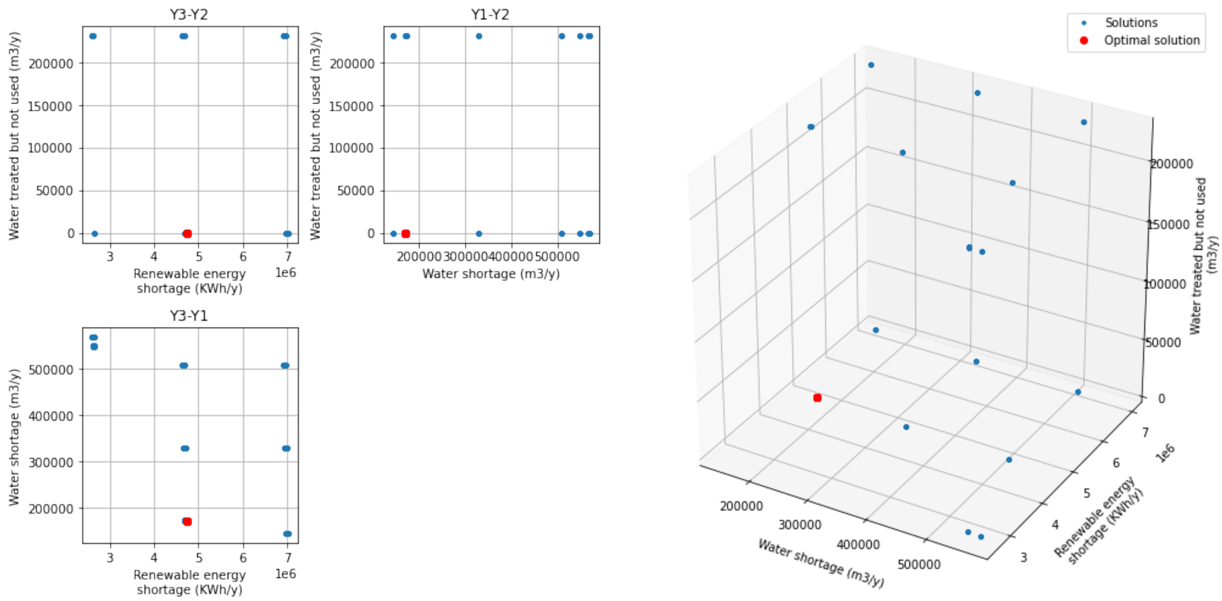

Figure 37. Multi-objective optimization results: Alternative 5.

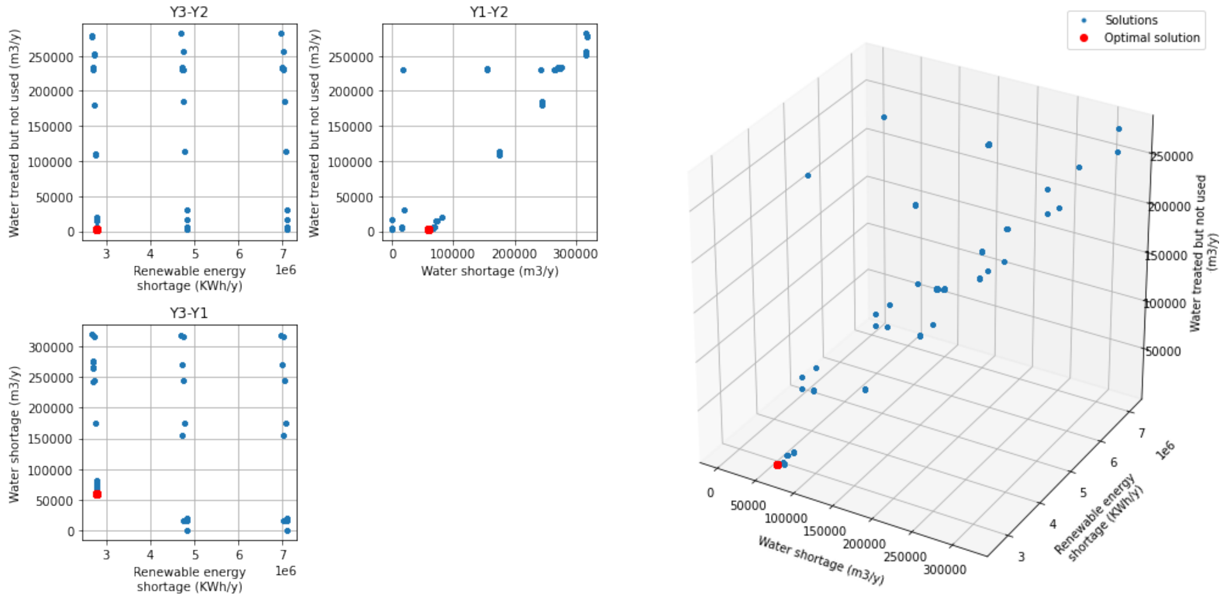

Figure 38. Multi-objective optimization results: Alternative 6.

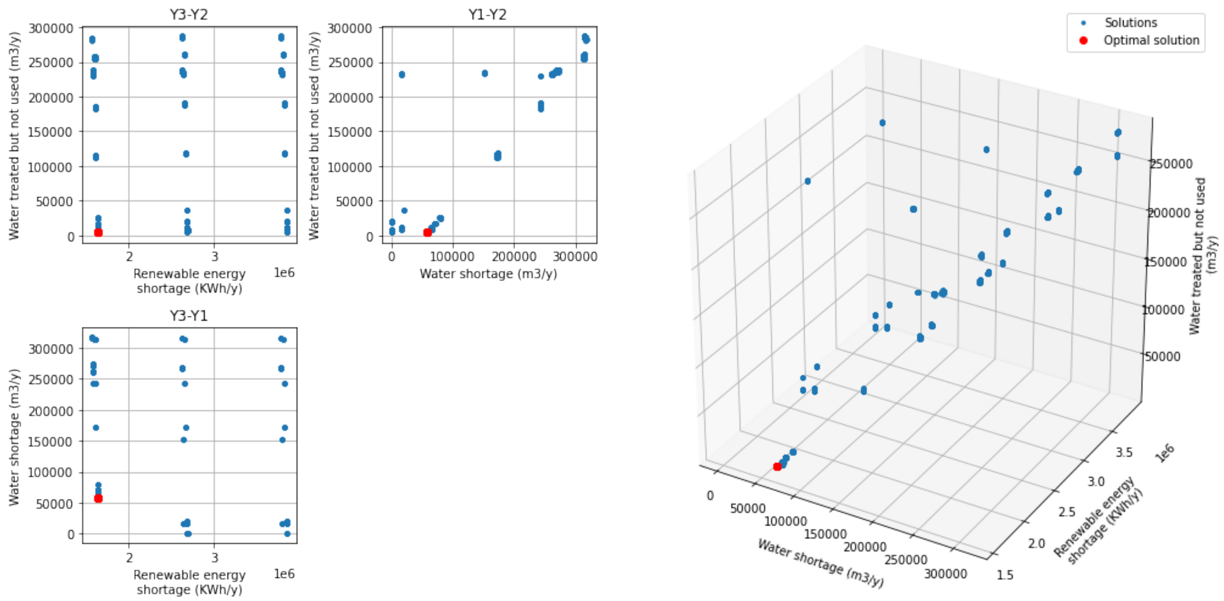

Figure 39. Multi-objective optimization results: Alternative 7.

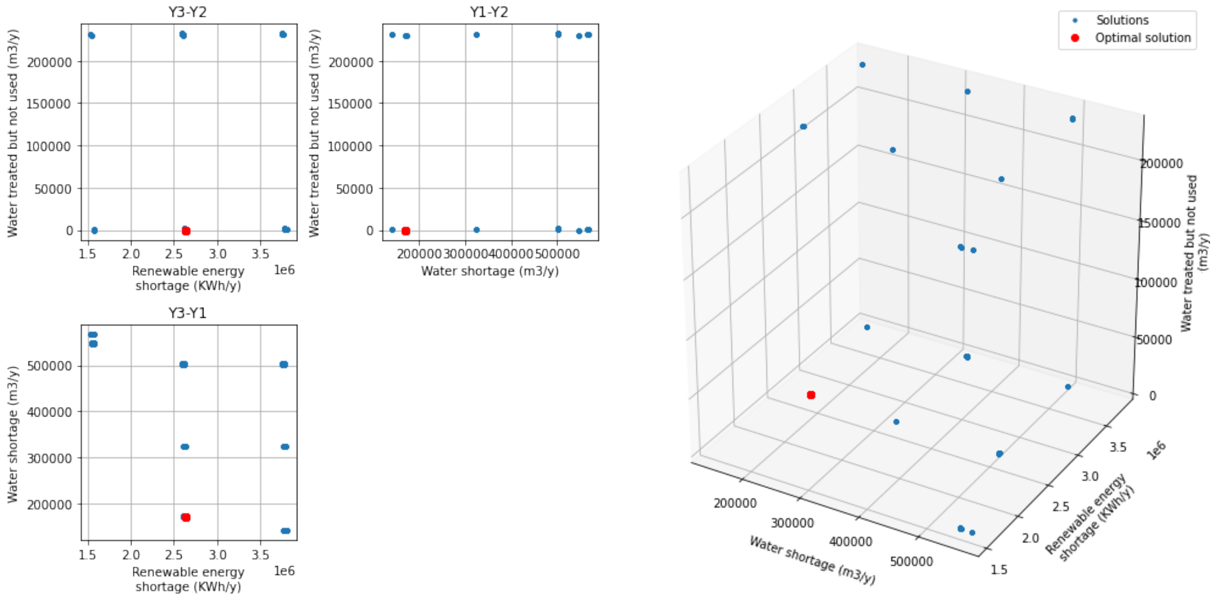

Figure 40. Multi-objective optimization results: Alternative 8.

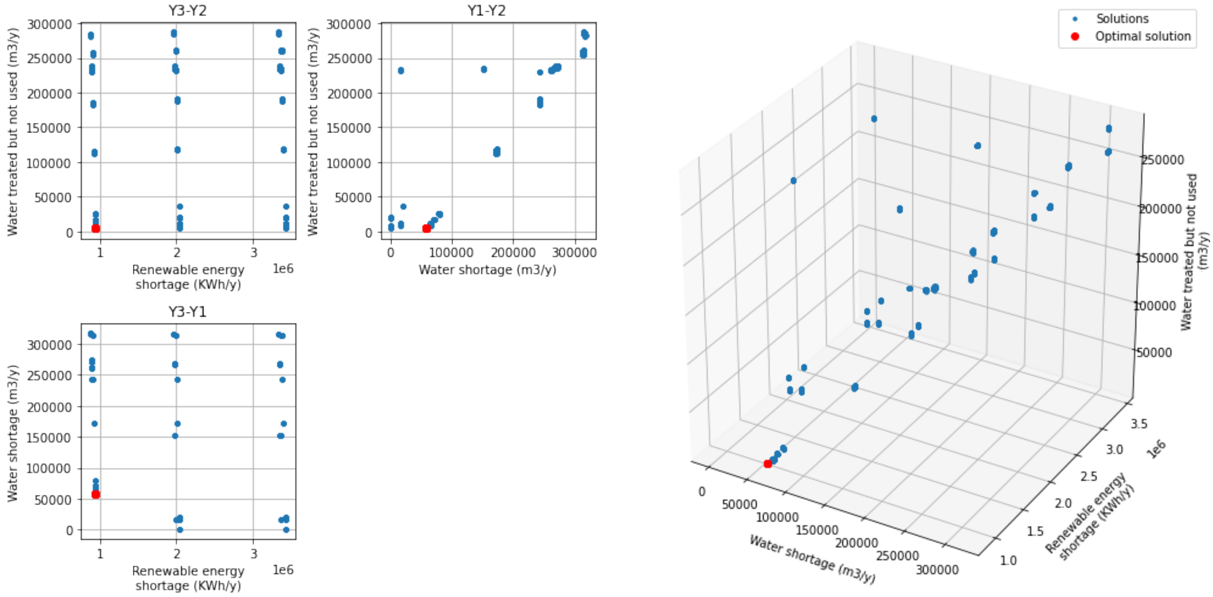

Figure 41. Multi-objective optimization results: Alternative 9.

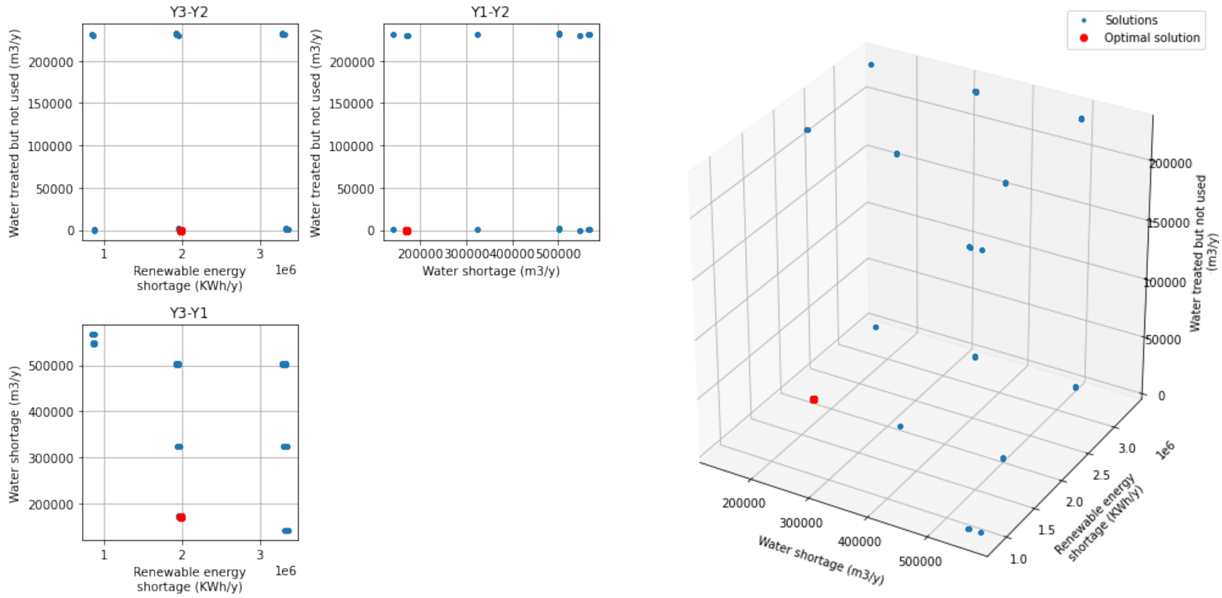

Figure 42. Multi-objective optimization results: Alternative 10.

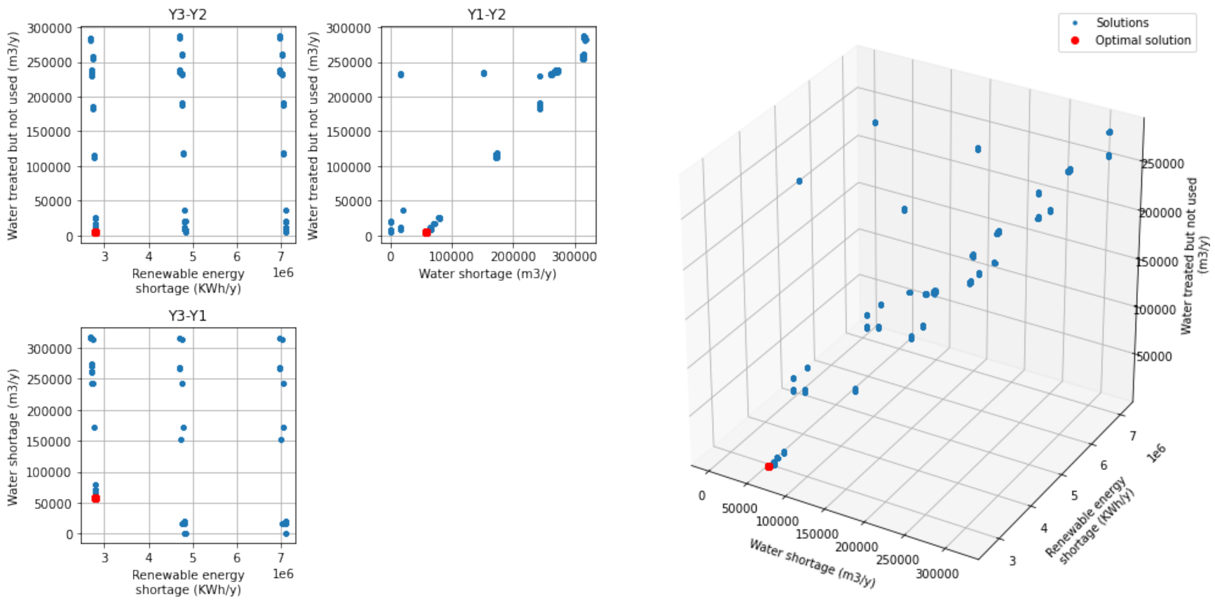

Figure 43. Multi-objective optimization results: Alternative 11.

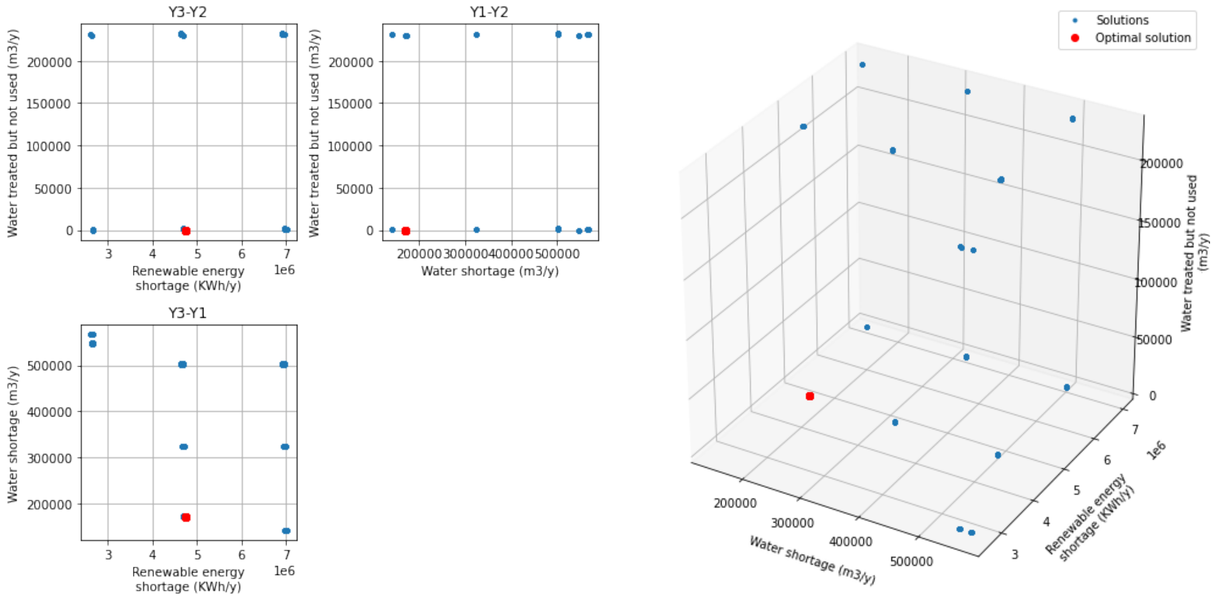

Figure 44. Multi-objective optimization results: Alternative 12.

Appendix V : Extrapolation of the costs from the model CoP cost calculator

Water Storage Tanks: The capital and operational costs are extrapolated from the model CoP cost calculator [51]. The functions to calculate the costs are:

$$Capital\ cost_{water\ tanks} = 4{,}356.9\ V^{0.7512} \tag{13}$$

$$Operation\ cost_{water\ tank} = 25.995\ V + 11{,}180 \tag{14}$$

Where capital and operational costs are expressed in euros (EUR), and V is the water tank storage volume *(m^3)*.

Table 56. Capital and operational costs for different water storage tank volumes (source:[51]).

Volume (m^3)	Capital cost (euros)	Operational cost (euros)
600	528,435.00 €	2,922.00 €
673.2	577,382.00 €	31,540.00 €
712.8	603,899.00 €	32,800.00 €
752.4	629,977.00 €	34,040.00 €
990	778,695.00 €	41,090.00 €
1180	894,524.00 €	46,585.00 €
1386	1,004,673.00 €	51,810.00 €
1782	1,211,800.00 €	61,634.00 €
2178	1,405,440.00 €	70,820.00 €
2970	1,763,740.00 €	87,820.00 €
3762	2,094,115.00 €	103,485.00 €

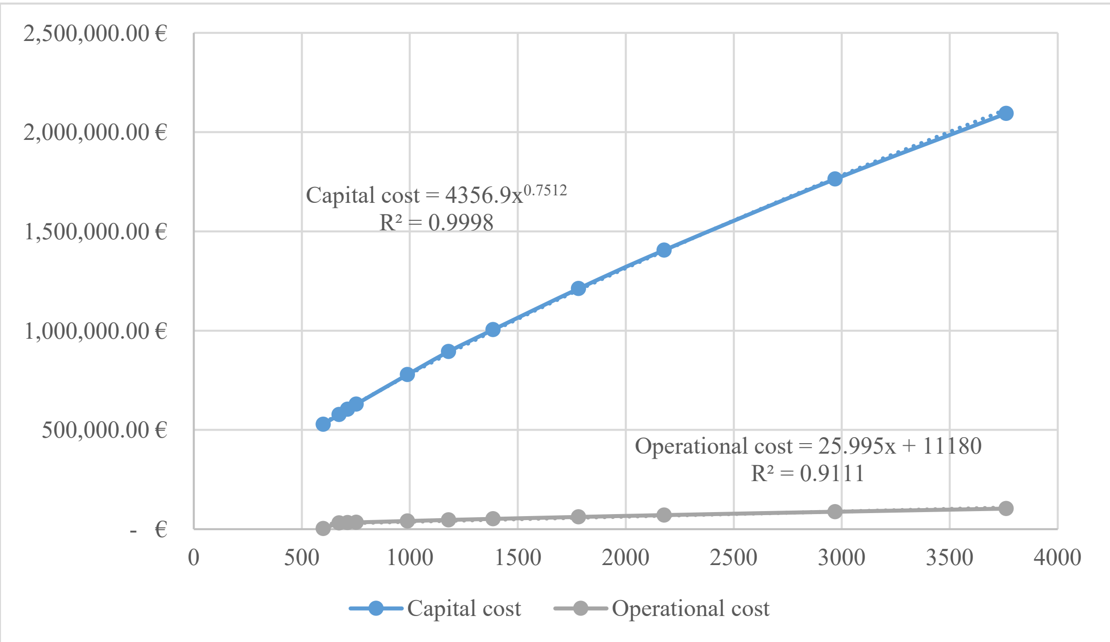

Figure 45. Trend lines for the capital and operational costs for different water storage tank volumes (source:[45]).

Pumping stations: The capital and operational costs are extrapolated from the model CoP cost calculator [51]. The functions to calculate the costs are:

$$Capital\ cost_{pumping\ stations} = 17{,}763\ Q^{0.7581} \tag{15}$$

$$Operation\ cost_{pumping\ stations} = 1{,}201.3\ Q^{0.7948} \tag{16}$$

Where capital and operational costs are expressed in euros (EUR), and Q is the pumping station capacity *(m^3/h)*.

Table 57. Capital and operational costs for different pumping capacities (source:[45]).

Volume (m^3/h)	Capital cost (euros)	Operational cost (euros)
600	2,268,956.00 €	193,991.00 €
700	2,548,253.00 €	219,133.00 €
800	2,820,086.00 €	243,693.00 €
900	3,085,558.00 €	267,758.00 €

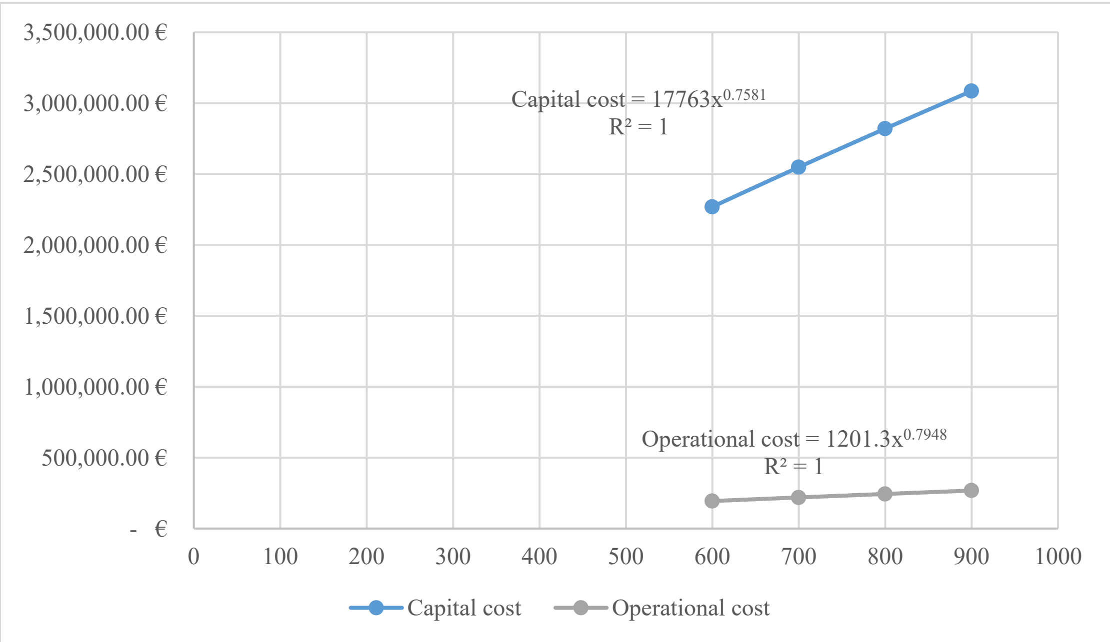

Figure 46. Trend lines for the capital and operational costs for different pumping capacities (source:[45]).

Appendix VI : Electricity demand for other services

Table 58. Other service's electricity demand excluding the urban water cycle (source: GFA Grupo Inmobiliario SC, personal communication, December 9, 2021).

	Area	Quantity	Units	Guests per room	Guests per unit	No. Inhab	Estimated unitary load (kVA)	Estimated total load (kVA)	Estimated total demanded load (kVA)
ESTATE LOTS	**ESTATE LOTS**					**1,380**		**2,470.00**	**1,482.00**
	TYPICAL VILLAS	**116**	**units**			**1,380**		**2,470.00**	**1,482.00**
	Five Bedroom Villa	36	units	2.0	10	360	20	720.00	432.00
	Six Bedrooms Villa	50	units	2.0	12	600	20	1,000.00	600.00
	Seven Bedroom Villa	30	units	2.0	14	420	25	750.00	450.00
RESORT	**RESORT**					**1,029**		**2,695.00**	**2,156.00**
	STANDARD ROOMS	**37**	**keys**			**194**		**425.00**	**340.00**
	STANDARD ROOM	10	keys	3.0	6	60	10	100.00	80.00
	TWO STORY STANDARD	8	keys	3.0	6	48	15	120.00	96.00
	EXECUTIVE VILLA	5	keys	2.0	4	20	10	50.00	40.00
	ONE BEDROOM SUITE	10	keys	2.0	4	40	10	100.00	80.00
	TWO BEDROOM SUITE	1	keys	3.0	6	6	10	10.00	8.00
	PRESIDENTIAL SUITE	1	keys	2.0	8	8	25	25.00	20.00
	OVERLAND SUITE	2	keys	3.0	6	12	10	20.00	16.00
	OVERWATER	**17**	**keys**			**38**		**195.00**	**156.00**
	STANDARD	14	keys	2.0	2	28	10	140.00	112.00
	ESTÁNDAR WITH LOCK OFF	1	keys	2.0	4	4	20	20.00	16.00
	ONE BEDROOM SUITE	1	keys	2.0	2	2	10	10.00	8.00
	TWO BEDROOM SUITE	1	keys	2.0	4	4	25	25.00	20.00
	BRANDED RESIDENTIAL	**24**	**units**			**144**		**510.00**	**408.00**
	Two Bedroom	6	units	2.0	4	24	20	120.00	96.00
	Three Bedroom	12	units	2.0	6	72	20	240.00	192.00
	Four Bedroom	6	units	2.0	8	48	25	150.00	120.00
	PUBLIC AREAS	**3611**	**m2**			**635**		**1,500.00**	**1,200.00**
	Lobby @ Main Building	29	m2		4	4	500	500.00	400.00
	FamilyClub	427	m2		100	100	100	100.00	80.00
	Pools restrooms	47	m2		8	8	3	2.50	2.00
	Lawn Area	33	m2		8	8	3	2.50	2.00
	Meal restaurant/pool side bar	457	m2		100	100	125	125.00	100.00
	Main Kitchen	550	m2		30	30	125	125.00	100.00
	Staff Dinning	188	m2		100	100	75	75.00	60.00
	Adult Pool Bar and grill	273	m2		50	50	125	125.00	100.00
	Service bar+storage MEP offices	44	m2		8	8	10	10.00	8.00
	Kids for all Seasons	44	m2		25	25	30	30.00	24.00
	Specialty Restaurant	198	m2		100	100	200	200.00	160.00
	Spa	1222	m2		100	100	200	200.00	160.00
	Retail	100	m2		2	2	5	5.00	4.00
	BOH					**18**		**65.00**	**52.00**
	Housekeeping stations guestrooms	5	units		5	5	10	50.00	40.00

	Housekeeping stations residences	1	units		10	10	10	10.00	8.00
	Front Office	80	m2		3	3	5	5.00	4.00
MARINA	**MARINA**					**462**		**1,102.50**	**771.75**
	BRANDED RESIDENTIAL	**13**	**units**			**106**		**310.00**	**217.00**
	Four Bedroom	12	units	2.0	8	96	25	300.00	210.00
	Housekeeping stations residences	1	units		10	10	10	10.00	7.00
	PUBLIC AREAS	**1011**	**m2**			**139**		**525.00**	**367.50**
	Marina reception Pavilion	203	m2		20	20	15	15.00	10.50
	Resort Main Building Lobby	65	m2		4	4	5	5.00	3.50
	Front Office	14	m2		3	3	3	2.50	1.75
	Beach Club		m2		8	8	75	75.00	52.50
	Park		m2		6	6	3	2.50	1.75
	Retail	100	m2		2	2	5	5.00	3.50
	Fitness	260	m2		5	5	10	10.00	7.00
	Event facilities-funtion rooms		m2		35	35	25	25.00	17.50
	Event facilities-Ballroom and outdoor event space		m2		20	20	25	25.00	17.50
	Event and meeting room		m2		4	4	25	25.00	17.50
	Banquet Kitchen		m2		8	8	225	225.00	157.50
	Nat Geo	300	m2		10	10	50	50.00	35.00
	Dive Centre Marine Discovery Centre, Sports	337	m2		10	10	50	50.00	35.00
	Security & Loading Dock		m2		4	4	10	10.00	7.00
	F&B OUTLETS	**409**	**m2**			**217**		**267.50**	**187.25**
	General Store & Bakery	64	m2		12	12	225	225.00	157.50
	Bar & Lounge	50	m2		65	65	3	2.50	1.75
	Bar & Lounge PANTRY		m2		5	5	5	5.00	3.50
	Bar/ Lobby Lounge /Coffee Bar (40s interior)	80	m2		40	40	5	5.00	3.50
	Young Adults	185	m2		35	35	20	20.00	14.00
	Golf Bar & Grill (10s interior + 50s exterior)	30	m2		60	60	10	10.00	7.00
BOH BUILDINGS	**BOH BUILDINGS**					**131**		**935.00**	**841.50**
	GENERAL	**7234**	**m2**	**-**		**131**		**935.00**	**841.50**
	Administration	1541	m2		30	30	150	150.00	135.00
	Finance	629	m2		6	6	75	75.00	67.50
	Security	447	m2		10	10	75	75.00	67.50
	Human Facilities	707	m2		15	15	150	150.00	135.00
	Staf Housein (On-Island)	3064	m2		40	40	225	225.00	202.50
	Houskeeping	286	m2		10	10	10	10.00	9.00
	Laundry	350	m2		10	10	100	100.00	90.00
	Food Service + Loading Docks	210	m2		10	10	150	150.00	135.00
GOLF	**GOLF**					**311**		**460.00**	**276.00**
	PUBLIC AREAS	**576**	**m2**	**-**		**147**		**420.00**	**252.00**
	Golf Clubhouse	290	m2		15	15	25	25.00	15.00
	Restaurant	50	m2		50	50	200	200.00	120.00
	2 Confort Station + restaurant		m2		50	50	100	100.00	60.00
	Administration offices+trabajadores	45	m2		15	15	75	75.00	45.00
	Maintenance golf	45	m2		5	5	5	5.00	3.00
	Farm		m2		7	7	5	5.00	3.00
	Pro Shop /Retail	146	m2		5	5	10	10.00	6.00

STAFF HOUSING	**154**	**units**	**-**		**164**	**150**	**40.00**	**24.00**
Management Compound	5	units	1	5	5	3	2.50	1.50
Non Management	64	units	1	64	64	3	2.50	1.50
Temporary Facilities	72	units	1	72	72	3	2.50	1.50
Administration	5	units	1	5	5	3	2.50	1.50
Doctor's Office	8	units	1	8	8	10	10.00	6.00
Maintenance				10	10	20	20.00	12.00
				TOTAL	*3,313*		*7,662.50*	*5,527.25*
						The estimated electric demand is	***5,527.25***	kVA/d

Appendix VII : Code's nomenclature

The model was developed in Python. Table 59 shows the different variables that integrate the code, their description and units.

Table 59. Code's nomenclature.

NO.	NOMENCLATURE	DESCRIPTION	UNITS
GENERAL PARAMETER			
1	days	Number of days that will be modeled.	days
2	hours	Number of hours per day.	hours
INPUT			
3	water_demand_pot_daily	Average inhabitants' daily water demand.	m^3/d
4	PF_hourly	Hourly peak factor.	adim
5	PF_monthly	Monthly peak factor.	adim
6	water_demand_pot_hourly	Hourly inhabitants' water demand.	m^3/h
7	water_demand_irrig_daily	Average irrigation daily water demand.	m^3/d
8	irrig_t_hours	Number of hours that the irrigation system operates per day.	hours
9	irrig_t_starting	Daily time at which the irrigation system starts to operate.	hours
10	water_demand_irrig_hourly	Hourly irrigation water demand.	m^3/h
11	P	Precipitation hourly data.	m/h
12	Ev	Evaporation hourly data.	m/h
13	Ws	Wind speed hourly data @10 m relative to the surface.	m/s
14	Sr	Solar irradiance.	W/m^2
(DWTP) DRINKING WATER TREATMENT PLANT			
15	seawater_t_production_starting	Daily time at which the desalination facility starts to operate.	hours
16	seawater_t_production_hours	Number of hours that the desalination facility operates per day.	hours
17	dwtp_Q_capacity	Maximum hourly capacity.	m^3/h
(DWT) DRINKING WATER STORAGE TANK			
18	dwt_V_max	Maximum storage capacity.	m^3
19	dwt_V_per_low	Indicator for low percentage of stored water.	adim
20	dwt_V_full	Available water in the water tank.	m^3
21	dwt_V_per	Percentage of available water in the water tank.	%
22	dwt_V_empty	Available storage capacity in the water tank.	m^3
23	dwt_Q_out_pot	Water flow going to the potable services.	m^3/h
24	dwt_Q_out_irrig	Water flow going to the IWT.	m^3/h
25	dwt_Q_in	Water flow coming into the tank.	m^3/h
(WWTP) WASTEWATER TREATMENT PLANT			
26	ww_factor	Percentage of drinking water that becomes wastewater.	%
27	wwtp_factor	Percentage of treated wastewater produced per cubic meter of wastewater entering the WWTP.	%
28	delay_dwt_wwtp	Amount of timespets required for one cubic meter of water to go from the DWT to the WWTP.	adim
29	delay_wwtp_wwt	Amount of timespets required for one cubic meter of wastewater to be converted into treated wastewater.	adim
30	wwtp_Q_capacity	Maximum hourly flow capacity.	m^3/h
31	wwtp_Q_in	Water flow coming in.	m^3/h
32	wwtp_Q_out	Water flow going out.	m^3/h

33	wwtp_Q_rejected	Water flow rejected (do nt go inside the WWTP).	m^3/h
(WWT) TREATED WASTEWATER STORAGE TANK			
34	wwt_V_max	Maximum storage capacity.	m^3
35	wwt_V_min	Minimum storage capacity.	m^3
36	wwt_Q_in	Water flow coming in.	m^3/h
37	wwt_Q_out_spill	Water flow spilled.	m^3/h
38	wwt_Q_out_irrig	Water flow going to the IWT.	m^3/h
39	wwt_V_full	Available water in the water tank.	m^3
(WB) GOLF COURSE'S WATER BODIES			
40	wb_hh	The set level is defined as: wb_hh - wb_h_range.	m
41	wb_h_range	The overflow level is defined as: wb_hh + wb_h_range	m
42	wb_area	Surface area.	m
43	wb_h_min	Minimum water level.	m
44	wb_h	Water level.	m
45	wb_Q_in	Water flow coming in.	m^3/h
46	wb_Q_out	Water flow overflowed.	m^3/h
47	wb_Q_in_demand	Water flow that is required to keep the set water level.	m^3/h
(RWB) RAINWATER BUFFER TANK			
48	delay_wb_rwb	Amount of timespets required for one cubic meter of rainwater to flow from the WB to the RWB.	adim
49	rwb_V_max	Maximum storage capacity.	m^3
50	rwb_V_min	Minimum storage capacity.	m^3
51	rwb_V_full	Available water in the water tank.	m^3
52	rwb_V_empty	Available storage capacity in the water tank.	m^3
53	rwb_Q_in	Water flow coming in.	m^3/h
54	rwb_Q_out_spill	Water flow spilled.	m^3/h
55	rwb_Q_out_irrig	Water flow going the RWT.	m^3/h
(RWTP) RAINWATER TREATMENT PLANT			
56	rwtp_factor	Percentage of treated rainwater produced per cubic meter of rainwater entering the RWTP.	%
57	delay_rwtp_rwt	Amount of timespets required for one cubic meter of rainwater to be converted into treated rainwater.	adim
58	rwtp_Q_capacity	Maximum hourly flow capacity.	m^3/h
59	rwtp_Q_in	Water flow coming in.	m^3/h
60	rwtp_Q_out	Water flow going out.	m^3/h
(RWT) RAIN WATER STORAGE TANK			
61	rwt_V_max	Maximum storage capacity.	m^3
62	rwt_V_min	Minimum storage capacity.	m^3
63	rwt_Q_in	Water flow coming in.	m^3/h
64	rwt_Q_out_spill	Water flow spilled.	m^3/h
65	rwt_Q_out_irrig	Water flow going to the IWT.	m^3/h
66	rwt_V_full	Available water in the water tank.	m^3
(IWT) IRRIGATION AND RECOVERY WATER STORAGE TANK			
67	iwt_V_max	Maximum storage capacity.	m^3
68	iwt_V_min	Minimum storage capacity.	m^3
69	iwt_V_per_low	Indicator for low percentage of stored water.	m^3
70	iwt_V_per_med	Indicator for medium percentage of stored water.	m^3
71	iwt_V_per_high	Indicator for high percentage of stored water.	m^3
72	iwt_P_min	Minimum precipitation's treshold to shut down the irrigation system.	m
73	iwt_V_full	Available water in the water tank.	m^3

74	iwt_V_empty	Available storage capacity in the water tank.	m^3
75	iwt_V_per	Percentage of available water in the water tank.	m^3
76	iwt_Q_in_wwt	Water flow coming in from the WWT.	m^3/h
77	iwt_Q_in_rwt	Water flow coming in from the RWT.	m^3/h
78	iwt_Q_in_dwt	Water flow coming in from the DWT.	m^3/h
79	iwt_Q_out_wb	Water flow going to the WB.	m^3/h
80	iwt_Q_out_irrig	Water flow going to the irrigation system.	m^3/h
81	iwt_Q_out_spill	Water flow spilled.	m^3/h
PUMPING STATIONS			
82	dwt_Q_out_irrig_pump	Flow capacity of pumping station no. 1	m^3/h
83	wwt_Q_out_irrig_pump	Flow capacity of pumping station no. 4	m^3/h
84	rwb_Q_out_irrig_pump	Flow capacity of pumping station no. 5	m^3/h
85	rwt_Q_out_irrig_pump	Flow capacity of pumping station no. 6	m^3/h
86	rwt_Q_out_irrig_pump	Flow capacity of pumping station no. 7	m^3/h
87	iwt_Q_out_irrig_pump	Flow capacity of pumping station no. 8	m^3/h
88	iwt_Q_out_wb_pump	Flow capacity of pumping station no. 9	m^3/h
URBAN WATER CYCLE'S ELECTRICITY DEMAND			
89	pump_eff	Pumping station's efficiency.	%
90	pump_Q	Pumping station's hourly flow.	m^3/h
91	pump_set	Number of pumps in parallel for each pumping station.	adim
92	pump1_E	Electricity demand from the pumping station no.1	kW/h
93	pump2_E	Electricity demand from the pumping station no.2	kW/h
94	pump3_E	Electricity demand from the pumping station no.3	kW/h
95	pump4_E	Electricity demand from the pumping station no.4	kW/h
96	pump5_E	Electricity demand from the pumping station no.5	kW/h
97	pump6_E	Electricity demand from the pumping station no.6	kW/h
98	pump7_E	Electricity demand from the pumping station no.7	kW/h
99	pump8_E	Electricity demand from the pumping station no.8	kW/h
100	pump9_E	Electricity demand from the pumping station no.9	kW/h
101	dwtp_E	Electricity demand from the DWTP.	kW/h
102	wwtp_E	Electricity demand from the WWTP.	kW/h
103	rwtp_E	Electricity demand from the RWTP.	kW/h
104	water_E_demand	Urban water cycle's electricity demand.	kW/h
(WT) WIND TURBINES			
105	wt_z	Hub's height.	m
106	wt_capacity	Rated capacity.	kWh
107	wt_quantity	Number of wind turbines.	adim
108	wt_E_out	Electricity delivered by the wind turbine(s).	kWh
(PV) PV PANELS			
109	pv_A	Area of PV panels.	m^2
110	pv_yield	Yield.	%
111	pv_tf	Transposition factor.	adim
112	pv_pf	Performance factor.	%
113	pv_E_out	Electricity delivered by the PV panels.	kWh
(IRE) INTERMITTENT RENEWABLE ENERGY			
114	ire_E	Intermittent renewable energy.	kWh
115	ire_E_grid	Intermittent renewable energy going into the urban water cycle's grid.	kWh
116	ire_E_stor	Intermittent renewable energy going into the battery.	kWh
117	ire_E_rejected	Intermittent renewable energy rejected.	kWh
(BT) BATTERY			

118	b_eff	Battery's efficiency.	%
119	b_stor_capacity	Maximum storage capacity.	kW
120	b_in_capacity	Maximum inlet capacity.	kWh
121	b_out_capacity	Maximum outlet capacity.	kWh
122	b_E_full	Available energy stored in the battery.	kW
123	b_E_empty	Available storage capacity in the battery.	kW
124	b_E_out	Electricity delivered by the battery.	kWh
125	b_E_in	Energy coming into the battery.	kWh

Appendix VIII : Structure of the matrix "m" from the model

The models can give as an output the matrix "m" with dimensions 26 x 2. The structure is shown in Table 60.

Table 60. Structure of the matrix "m".

PERFORMANCE	POSITION IN THE MATRIX	
Water		% Time
Production:		
Potable water production (m^3)	0, 0	/
Non potable water production (m^3)	1, 0	/
from rainwater	2, 0	/
from wastewater	3, 0	/
Demand:		
Inhabitants water demand (m^3)	5, 0	/
Irrigation water demand (m^3)	6, 0	/
Shortage:		
Inhabitants water shortage (m^3)	8, 0	8, 1
Irrigation water shortage (m^3)	9, 0	9, 1
Water bodies below the minimum level (%)	/	10, 1
Spillage/rejected:		
Rainwater (m^3)	12, 0	12, 1
Treated rainwater (m^3)	13, 0	13, 1
Treated wastewater (m^3)	14, 0	14, 1
Irrigation tank (m^3)	15, 0	15, 1
Wastewater rejected (m^3)	16, 0	16, 1
Energy		
Renewable Energy production (kW)	18, 0	/
Energy demand (kW)	19, 0	/
Renewable energy shortage (kW)	20, 0	20, 1
Renewable energy rejected (kW)	21, 0	21, 1
Daily RES penetration (%):		
Minimum	23, 0	/
Average	24, 0	/
Maximum	25, 0	/

Appendix IX : Structure of the matrix "R" from the model

The models can give as an output the matrix "m" with dimensions 12 x 1. The structure is shown in Table 61.

Table 61. Structure of the matrix "R".

PERFORMANCE	POSITION IN THE MATRIX
For Water:	
Water shortage (m^3/month)	0, 0
Percentage of time with water shortage (%)	1, 0
Percentage of time with the water level from the water bodies below the set level (%)	2, 0
Water treated but not reused (m^3/month)	3, 0
For Energy:	
Renewable Energy production (MW/month)	5, 0
Energy demand (MW/month)	6, 0
Renewable energy shortage (MW/month)	7, 0
Renewable energy rejected (MW/month)	8, 0
Average daily RES penetration (%):	9, 0
ENVIRONMENTAL	
GHG emissions (10^3 kg CO_2-eq /year)	11, 0