Pathway to a sustainable and self-sufficient UNAM campus in Sisal

CEGM3000: Multidisciplinary Project (MDP)

Ole Siepman, Joppe de Vos, Sjoerd Houben, Sjoerd Koopman, Julie van Ouwerkerk and Boaz van Lith

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CEGM3000: Multidisciplinary Project

by

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Preface

This report is the result of a multidisciplinary project (CEGM3000) conducted at the National Autonomous University of Mexico (UNAM) in Sisal, from September to November 2025. The project emerged from the ongoing collaboration between Delft University of Technology and UNAM. As a team of six master's students, we worked together to develop a pathway towards a more sustainable and self-sufficient campus.

By combining our diverse academic backgrounds and perspectives, we aimed to provide a comprehensive understanding of the infrastructural and environmental challenges facing the campus. We have focused on integrated solutions for the domains of energy, water, and waste. This report is intended for anyone interested in sustainable campus development and the practical application of sustainability solutions in a coastal environment.

We express our sincere gratitude to our supervisors at UNAM, Dr. A.T. Freyermuth and Dr. M. E. Allende Arandía, for their invaluable guidance and support throughout this project. We also extend our thanks to our supervisors at TU Delft, J.A. Antolínez, M.J.J. Buijs, A.J. Laguna, and J.N. Quist, for their continuous support and insightful advice, which enriched the quality of our project. Additionally, we are grateful to the FAST University Fund for their valued financial support.

A special thanks goes to all the stakeholders, staff, students, and community members of Sisal for their time and perspectives, which gave us valuable insights into realities faced by the campus. We hope this report contributes to the ongoing efforts to transform the UNAM Sisal campus into a model for sustainability and self-sufficiency.

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Summary

The UNAM Sisal campus, situated in a remote and ecologically sensitive coastal region of Yucatán, faces significant challenges regarding sustainability and self-sufficiency. Its dependency on unreliable external infrastructure for energy and water, coupled with inadequate wastewater treatment and unstructured waste management, makes the campus vulnerable to environmental challenges and hinders its potential as a model for sustainable development. This multidisciplinary project aimed to address these issues by developing an integrated roadmap toward a self-sufficient and sustainable campus by 2035.

Using a methodological framework combining backcasting and design science principles, the study integrated stakeholder input (staff interviews, student surveys), technical data analysis, literature reviews, and expert consultations. Potential solutions across the domains of energy, water, and waste were systematically evaluated using Multi-Criteria Analysis (MCA) weighted by stakeholder preferences.

The findings indicate a clear pathway forward. For energy, prioritizing solar photovoltaic (PV) installations is recommended due to high local potential and scalability, contingent on initial detailed energy consumption monitoring. For water, the focus should be on implementing robust wastewater treatment to meet regulatory standards, followed by longer-term integration of small-scale desalination and supplementary rainwater/AC condensate harvesting. For waste, the primary step involves quantifying waste streams, followed by implementing an organizational strategy, such as a Zero Waste Grassroots Programme with source separation, composting, and partnerships for recycling.

The research ends with a phased roadmap outlining concrete short-, medium-, and long-term actions across all three domains. Successful implementation can transform the UNAM Sisal campus into a resilient, self-sufficient facility and a valuable example for sustainable practices in other coastal communities, though success depends on institutional commitment, securing funding, and establishing continuous monitoring.

Future research should focus on collecting reliable on-site data, testing pilot projects, and strengthening institutional frameworks to ensure long-term implementation, funding, and monitoring.

Keywords: *Sustainability, Self-sufficiency, University Campus, Coastal Environment, Sisal, UNAM, Energy Systems, Water Management, Waste Management, Renewable Energy, Solar PV, Wastewater Treatment, Multi-Criteria Analysis (MCA), Backcasting, Roadmap.*

Contents

1

Introduction

Sisal, a small fishing town on the northern coast of the Yucatán Peninsula, sits where land, sea, community and education meet within one of Mexico's most ecologically sensitive regions. The area is characterized by beaches, mangroves, dunes, and wetlands that form an interconnected and fragile ecosystem (Figure 1.1). Despite its natural richness, Sisal faces increasing environmental pressure due to climate change, development, and growing human activity.

Designated as a Pueblo Mágico (Magical Town) in 2020 to highlight its cultural and ecological value (Cruz et al., 2024), Sisal has since experienced growing interest in tourism and investment. This has created opportunities for local development but also intensified the pressure on its limited infrastructure, resources and natural systems.

Figure 1.1: Areal Picture of Sisal in 2023 (Rosado Van Der Gracht, 2023)

Rising sea levels, stronger storms, and saline intrusion threaten all human activities in the region including the UNAM Sisal Campus. The campus, located near the town of Sisal, plays a key role in research on those problems within coastal engineering and environmental sciences (Herrera-Silveira, 2009). Adding onto this, the Campus is isolated and is approximately 60 km from Mérida, the nearest major city. As a result, its dependence on external infrastructure, services and resources for energy, water and waste management increases (Martínez, 2025).

As a result of its location and external developments previously described the campus is facing significant challenges:

- **Energy**: The campus is largely dependent on electricity from Mérida, which is unreliable and often subject to outages. In the event of power failure, the campus relies on diesel generators, which is both costly and environmentally damaging. The lack of a stable, renewable energy infrastructure increases the campus's vulnerability to energy disruptions, especially in light of growing environmental concerns (Silinto et al., 2025).
- **Water**: Water availability is another critical challenge for the Sisal campus. Salinization of local groundwater due to the encroaching sea has affected the quality of water sources, leading to

concerns about the sustainability of water supply for both the campus and the local community. The campus is also reliant on local water systems that are prone to disruptions (Narvaez-Montoya et al., 2025).

- **Waste**: The campus currently faces inefficiencies in waste management, with limited infrastructure for sorting, recycling, and proper disposal of waste. As the campus continues to grow, waste management will become an increasingly critical issue, both for the university and the surrounding community (Armijo de Vega, 2006).
- **Infrastructure**: The infrastructure on campus is underdeveloped and often inadequate for current and future needs. This includes issues related to energy supply, water management, and waste disposal. While there are efforts underway to improve these systems, there remains a significant gap in terms of long-term sustainability planning and the necessary resources to address these gaps.
- **Storms and Flooding**: The campus is situated in an area susceptible to extreme weather events, including hurricanes and tropical storms. The rising frequency and intensity of these storms, exacerbated by climate change, present a direct threat to the campus's infrastructure, including buildings, roads, and power supply systems. Coastal flooding also affects the campus's vulnerability to storm surges (Lassiter, 2021).

These challenges, spanning environmental, infrastructural, resource-related, and socio-economic dimensions, have left the campus unable to operate sustainably or independently. At the same time, they offer a clear opportunity: the Sisal campus can serve as a pilot site for developing and implementing integrated sustainability solutions tailored to coastal environments. These environmental challenges are not the problems this study aims to solve directly, but rather the boundary conditions within which feasible and resilient solutions must be developed.

Therefore, the project aims to support the Sisal campus in addressing its sustainability and independence challenges through the development of a comprehensive sustainability plan. This report will present the results of a multidisciplinary project conducted within the Master's program at Delft University of Technology, in collaboration with the National Autonomous University of Mexico (UNAM).

The primary objective of this project is to develop a sustainability roadmap for the Sisal campus, integrating solutions for the domains of energy, water, and waste. While sustainability covers more domains, it was decided to focus on these three due to the timeline of the project, which was done in consultation with the project supervisor, Alec Torres. The project aims to transform the campus into a more self-sufficient facility, capable of adapting to environmental challenges, while also serving as a model for sustainable innovation that can be applied to other campuses and coastal communities. The project is guided by the following research question and objectives.

Research question:
How can the UNAM Sisal campus become a self-sufficient and sustainable campus through integrated energy, waste, and water solutions that are technical feasible and developed in alignment with stakeholder interests?

Project objectives:

- Develop a sustainability vision leading to a concrete and actionable plan for achieving a self-sufficient and sustainable campus.
- Assess the campus's energy, water, and waste systems to enhance self-sufficiency and sustainability.
- Assess renewable energy solutions for the campus's energy supply.
- Assess small-scale water systems to ensure a self-sufficient and sustainable water supply.
- Assess waste management strategies that minimise environmental impact and promote circular practices.
- Become an example for other coastal campuses in Mexico in sustainability and self-sufficiency.
- Establish a foundation for future sustainable initiatives.

The remainder of this report builds upon the research question and objectives. Chapter 2 outlines the methodological framework, describing the overall process followed throughout the project. Chapter 4 analyses the current state of the campus, identifying key bottlenecks, knowns and unknowns. Chapter 4 presents the long-term vision for 2035, which defines the strategic goals that guide the proposed solutions. Chapter 5 explores potential solutions within the energy domain, Chapter 6 focuses on the water domain, and Chapter 7 addresses waste management. Then, Chapter 8 presents a phased roadmap that translates these findings into concrete and actionable steps towards a self-sufficient and sustainable campus. Finally, Chapter 9 discusses the key findings and assumptions and provides recommendations for future research.

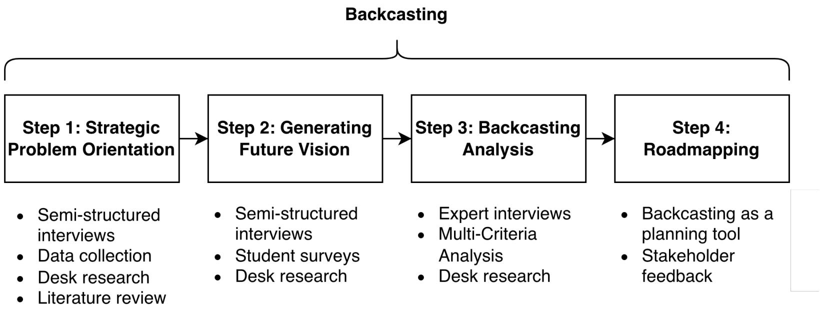
2
Methods

2.1. Research Purpose

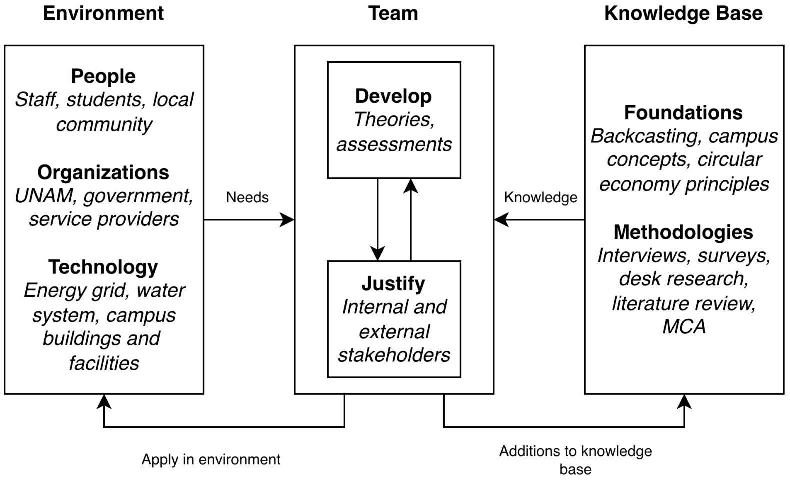
The aim of this research is to define a future vision for a sustainable and self-sufficient Sisal campus and translates that vision into concrete steps the campus can execute. It sets the scope and direction of change. It identifies the gap between the current and the desired state and determines the order of actions to close that gap. The outcome is a phased roadmap with actions that enable the campus to be ready for implementation and a clear basis for decision making.

2.2. Methodological Framework

The methodological framework followed an iterative structure inspired by both backcasting and design science. At each stage of the backcasting process (Figure 2.1a), different methods were applied to continuously integrate technical findings, stakeholder input, existing knowledge, and strategic reflection. In every stage of the backcasting process, we used the iterative principles of design science (Hevner et al., 2004), which focuses on developing and evaluating solutions based on observations of the environment (people, organisation, and technology) refined through a knowledge base of theories, frameworks, and data (Figure 2.1b).



(a) Backcasting Framework



(b) Design Science Framework

Figure 2.1: Methodological Framework

Within this framework, a multidisciplinary task group collaborated to combine expertise from civil engineering, mechanical engineering, complex systems engineering, and strategic product design, creating a multiperspective solution space. Rather than following a fixed sequence, the process evolved through overlapping cycles of analysis, evaluation, and discussion.

This framework integrates the stages of backcasting method more specifically with semi-structured interviews, data analyses, literature review, surveys, multi-criteria analysis (MCA), and roadmapping, while applying design science principles throughout these steps. Together, these methods form an iterative process that connects technical diagnosis with participatory evaluation and strategic planning.The linear structure of backcasting is adapted from Quist et al., 2006a. Although presented as linear, the process is in reality iterative and continuously evolving (Figure 2.1b). Findings were continuously reviewed as new information became available, resulting in adjustments to assumptions, priorities, and evaluation criteria throughout the duration of the project. The process gradually converged into a set of integrated solutions and, ultimately, into a roadmap connecting short- and long-term actions for the Sisal campus. The steps of the process, as shown in Figure 2.1a, are presented below.

Step 1: Strategic Problem Orientation

Four complementary methods were applied to map the current situation: Semi-structured interviews, data collection, a literature review and a desk study for grey literature. Semi-structured interviews with staff, students, and local stakeholders were used to collect qualitative insights into perceptions, barriers, and opportunities related to sustainability practices on campus. This method was selected because it combines structure and flexibility, allowing new perspectives to emerge while ensuring all core topics are addressed, an approach particularly suitable for exploratory sustainability research in institutional contexts (Kallio et al., 2016). Quantitative data was obtained from the ERA5 reanalysis dataset and scaled with available on-site measurements, as the local data was incomplete and lacked sufficient records to be used directly in the analysis. Then, a desk study was conducted based on the interview findings to identify and analyse relevant information from the UNAM database. Finally, a literature review was conducted to contextualise the campus situation within comparable cases and identify proven strategies for sustainability transitions in similar settings. Following the structured approach of Snyder (2019), academic sources were selected from Scopus and ScienceDirect. These combined results informed the assessment in Chapter 3.

Step 2: Generating Future Vision

The second step aimed to define the desired long-term vision for the Sisal campus. A new round of semi-structured interviews and student surveys was conducted to explore sustainability priorities and perceptions. The survey data gave an extra different perspective and complemented the findings. In addition, the UNAM sustainability statement was reviewed and combined with the stakeholder findings to form a shared vision and set of measurable goals. These goals were further validated through a desk research of global and regional sustainability frameworks, to ensure comparability with similar university initiatives. This step is presented in Chapter 4.

Step 3: Backcasting Analysis

The third step explored concrete pathways and solutions to achieve the established future vision, through an integrated combination of literature review, expert interviews and Multi-Criteria Analysis (MCA). The literature review identified a longlist of potential technological and organisational measures for energy, water, and waste systems. Targeted expert interviews with companies, researchers, and governmental representatives then refined these into feasible context-specific solutions. For al these solutions CAPEX, OPEX, potential yield and needed surface area were calculated. To evaluate and prioritise the shortlisted solutions, an MCA was applied, allowing assessment across technical, economic, environmental, and social criteria. The MCA method provides a transparent and structured way to balance multi-dimensional trade-offs and has been widely used in sustainability and infrastructure planning (Cinelli et al., 2014; Kumar et al., 2017). The criteria weighting was derived from stakeholder surveys, ensuring alignment between technical feasibility and local preferences. The criteria weighting is further elaborated in appendix H. The MCA results informed the solution recommendations in Chapters 5–7.

Step 4: Roadmapping

The final step synthesised the outcomes from all domains to design an integrated roadmap for implementation. Backcasting served as the overarching strategic planning tool, starting from the desired end-state and reasoning backward to identify required actions. This approach contrasts with forecasting by promoting transformative rather than incremental change (Quist et al., 2006a; Sisto et al., 2020). Stakeholder feedback from the previous steps was reintroduced to verify the feasibility and coherence of proposed actions. The resulting roadmap aligns short-, medium-, and long-term measures, linking them to the 2035 sustainability vision of the Sisal campus. This step integrates all findings into a coherent strategy presented in Chapter 8.

2.3. Data collection and analysis

Quantitative data

Quantitative data was used to assess the feasibility of the proposed solutions in the domains of energy and water. The wind and solar energy analyses were based on the ERA5 reanalysis dataset, which provides a 35-year hourly record but has limited local accuracy. To correct for these biases, the data was adjusted to local measurements using bias correction methods, resulting in more reliable environmental inputs for regional analysis. Appendix A describes the datasets, correction methods, and data processing steps in detail. For the water domain, data was obtained from two main sources: notes from the campus manager and the study by Sagastume (2022). The available data are based on monthly averages, which limits their usefulness for estimating peak demand. Moreover, the dataset only represents the central distribution point, making it impossible to analyse internal water flows. Although this information provides a valuable first approximation of the campus water system, its quality and resolution are limited.

Qualitative data

Qualitative data was collected through two methods: interviews and surveys. Semi-structured interviews were conducted with key stakeholders. Most interviews were recorded and subsequently transcribed using Turboscribe and can be found in Appendix E. The responses were then compiled and analysed. In addition, surveys were carried out using Google Forms to assess perceptions of sustainability and to establish weighting factors for the evaluation criteria. The perception survey included open-ended questions, whereas the weighting survey consisted of closed questions using a Likert scale to determine the relative importance of different criteria.

Literature Review

The literature review was conducted to identify sustainability strategies and technologies relevant to the Sisal campus. It focused on renewable energy, water management, waste reduction, and stakeholder engagement in universities with similar environmental and financial conditions. Following the structured approach proposed by Snyder (2019), studies were selected from the UNAM database as well as databases such as Scopus and ScienceDirect based on their direct applicability to campus-scale sustainability.

The review informed the selection of feasible interventions and the criteria used in the Multi-Criteria Analysis. Technical sources provided data on performance and costs, while social and governance studies added insight into implementation and acceptance. Together, these findings ensured that proposed solutions were evidence-based, context-specific, and aligned with the sustainability objectives of the Sisal campus.

2.4. Stakeholder Involvement

Stakeholder engagement is a key component of this research, as it is a proven strategy in university contexts (Antunes et al., 2006; Djukic-Min et al., 2025) and for the backcasting method (Quist et al., 2006a) for enhancing sustainability outcomes. Stakeholders were involved through several methods. Campus staff were interviewed to gain insight into their preferences and perceptions of sustainability, while students were invited to complete a survey exploring their views on sustainability. The input from both groups contributed to shaping the future vision and identifying potential solutions. These solutions were subsequently discussed with relevant experts to evaluate their feasibility and to define the steps required for implementation. Finally, campus coordinators were consulted again to assign weights to the evaluation criteria used in scoring potential solutions, allowing for the mapping and quantification of stakeholder preferences. All interviews and can be found in Appendix E. The corresponding transcripts and consent form can be found in the repository.

To ensure that all interview participants were fully informed about the collection and processing of their data, each participant was asked to sign an informed consent form prior to the interview. The form explained the purpose of the study, data handling procedures, and the option to either be named or remain anonymous in the report. Participation was entirely voluntary. Audio recordings of the interviews were used solely for transcription and analysis purposes.

3

Assessment of current situation

Prior to defining the future vision, it is necessary to create a clear baseline that make the campus as it is today. This baseline could potentially identify environmental, technical, and social challenges, but also highlights opportunities for improvement and areas where sustainability gains can be significant. First, the national and UNAM context is analysed, positioning the Sisal campus within this context. Then, the campus's location and accessibility are examined. Subsequently, the three domains energy, water, and waste are analysed, followed by a brief discussion of community and mobility aspects. Finally, the main findings are summarized.

3.1. National context

Mexico has adopted multiple environmental policies, focussed on waste management, renewable energy and climate change adaptation. However, research points to an implementation gap, where federal plans fail to convert itself to long-term local action. This could be due to challenges such as institutional fragmentation and uneven leadership (Solorio, 2021).

A relevant example of this can be found in the national waste management strategies. Mexico generates more than 100,000 tonnes of municipal solid waste per day, of which only 75%-80% reach formal disposal sites (Proyectos México, 2025). Local observations in Sisal confirm this: waste is often left on the streets or dumped in nearby mangroves. At the societal level, surveys show that Mexicans express concerns about climate change and environmental issues, but lack information, incentives, or support to act on this. 42% of the respondents on a national survey want to do more for the environment but do not know how, reflecting a knowledge action gap (Mitosfsky, 2024).

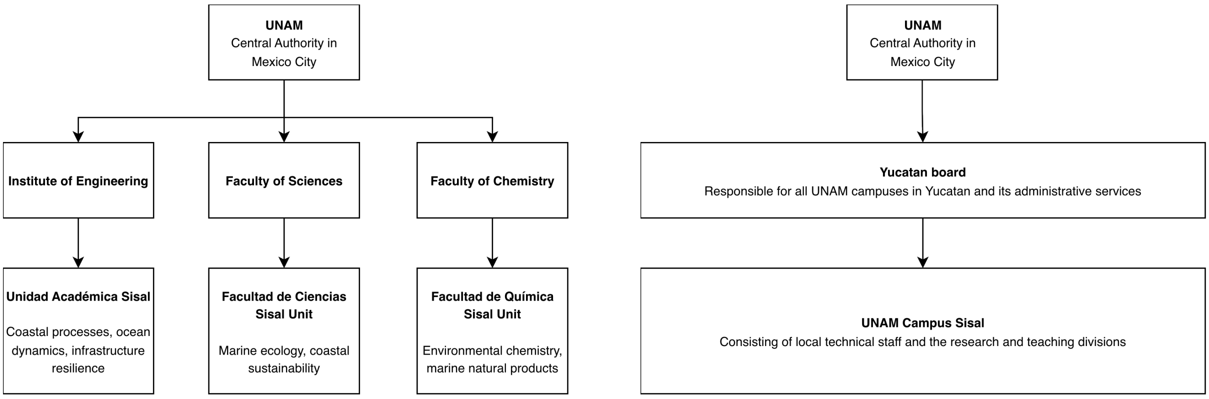
3.2. UNAM and stakeholders context

UNAM has an institutional strategy that assesses self-sufficiency and sustainability objectives (López, 2024). While these goals are ambitious and promising, the Sisal campus illustrates that such objectives have not yet been converted into concrete actions or projects, resulting in a similar outcome as with federal policies.

Internal stakeholders

The UNAM campus in Sisal is part of the wider organization of UNAM, the largest public university in Latin America. On a typical day, around 150 people are present, consisting of students, academics, and staff. Governance and budgets are decided centrally in Mexico City, while a regional directive board oversees the UNAM sites in Yucatán. This arrangement reduces local autonomy: important decisions require approval from the centre and often move through several administrative layers.

The Sisal campus brings together three entities: the Instituto de Ingeniería (Institute of Engineering), the Facultad de Ciencias (Faculty of Science), and the Facultad de Química (Faculty of Chemistry) (Figure 3.1). Academically, each reports to its parent faculty or institute in Mexico City. For operational issues, communication with the central authority runs through the UNAM Yucatán board. Locally, each division has its own director and staff. As a result, the campus does not operate under a single director but through parallel lines. This supports a multidisciplinary base, yet makes coordination of initiatives and innovation more complex. Figure 3.1a illustrates the academic hierarchy in Sisal which are managed by the three parent faculties in Mexico City. Figure (3.1b) shows the operational chain of command for management, finance, and infrastructure, which runs through the Yucatán Board. Together, they highlight the dual dependency of the campus on two separate governance lines, academic and operational, that rarely intersect. This report focusses on the operational structure of the Sisal campus, where potential improvements could be implemented, while the academic side remains a separate platform, possibly for demonstrating sustainable solutions.



(a) UNAM Academic structure

(b) UNAM Operational structure

Figure 3.1: UNAM Organizational Structure

Administrative support is provided through the Yucatán branch of UNAM's Administrative Service, which manages finances, procurement, and infrastructure. It is important to note that this branch, in collaboration with a campus such as Sisal, can allocate up to 2 million pesos for infrastructure improvements without requiring approval from the central organization in Mexico City. As confirmed by (Redacted), *"If you keep the amount under 2 million pesos, you can use local resources."* (Appendix E, Interview 3).

The organizational structure of the Sisal campus reflects both strengths and limitations. Its position within UNAM provides access to multidisciplinary expertise and institutional resources, and the academic side can serve as a showcase for sustainability pilots within the same context as the campus in Sisal. At the same time, the campus operates with fragmented governance and limited financial autonomy, which slows decision-making and complicates the implementation of sustainability initiatives.

External Stakeholders

Beyond the internal UNAM structure, the campus's daily operations and its ability to implement sustainable solutions are dependent on several key external actors. These stakeholders control essential services, set regulations, or represent the local community. These stakeholders, such as the Comision Federal de Electricidad (CFE), the municipal government, service companies, and regulatory bodies, are addressed in their associated domains below.

3.3. Location and Accessibility

The UNAM Sisal campus operates in a setting that presents several challenges for sustainable development as adressed in Chapter 1. Remoteness is one of the main challenges (Figure 3.2). Its distance from Mérida limits access to reliable utilities, services, resources and transportation. In 2017 a storm occurred flooding the road as well as the campus (Figure 3.3), causing the community of both the campus and Sisal to be 'locked' in Sisal for multiple days. This overall dependence on the road and services from Mérida, increases vulnerability during outages or extreme events such as storms.

(a) Entrance of the campus during storm event, May 4th 2017.

(b) Entrance of the campus under normal conditions, Octobre 24th 2025.

Figure 3.3: Entrance of the Sisal campus under storm and normal conditions.

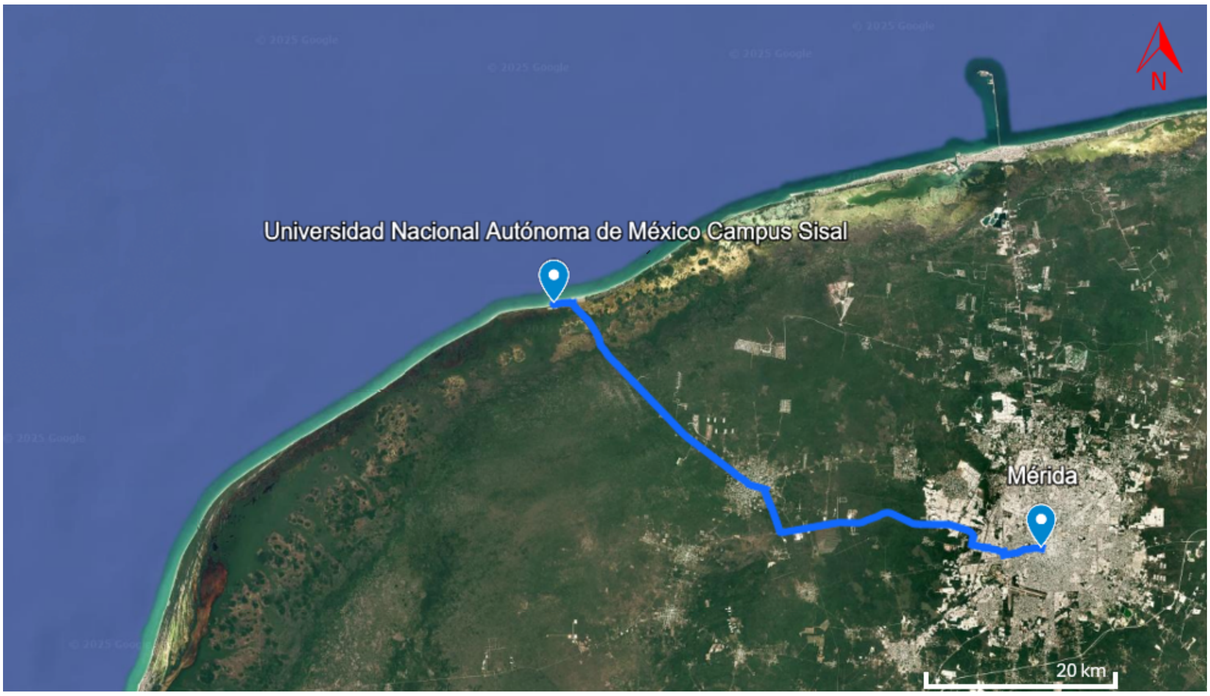


Figure 3.2: Map showing the distance between Sisal campus and Merida (55.87km)

In addition to remoteness, storms and flooding create an extra challenge. (Redacted) recalled a severe storm in 2025 that caused water levels to rise significantly across the entire campus: *”With big storms, the campus has flooded. A lot of times, you see boxes floating”* (Appendix E, Interview 1). The late arrival of warning signals left little time for preparations, resulting in damage to laboratories and equipment. Such events highlight how extreme weather can set back campus operations.

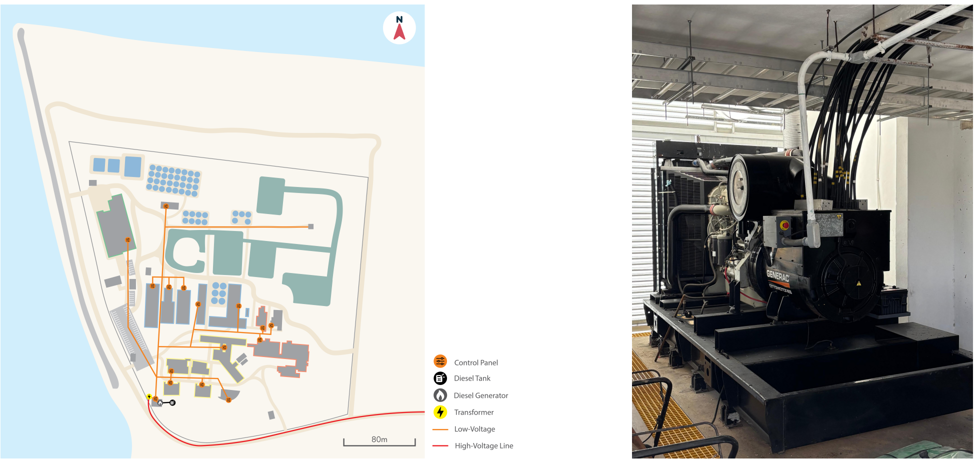
Now the location its external content is explained and its to environmental challenges, Figure 3.4 presents an overview of the Sisal campus. It shows the general configuration of buildings and key operational assets that are referenced throughout this chapter and are relevant to assessing the site’s vulnerabilities and infrastructure performance.

Figure 3.4: General map of campus

3.4. Domain-specific analyses of the campus

3.4.1. Energy

The Sisal campus depends entirely on electricity supplied from the national grid via the Comisión Federal de Electricidad (CFE). Power is transmitted from Mérida through Hunucmá before reaching Sisal and the campus. As the campus is located at the end of this distribution line, it experiences frequent instability issues, since demand along the route affects the quality of the supply. Moreover, any outage accident or storm-related damage along this route can result in a loss of power for Sisal, which was validated by stakeholders and observations. An overview of the current electricity grid of the campus is shown in Figure 3.5a.



(a) Electricity map of campus

(b) Diesel generator

Figure 3.5: Electricity map and generator

To mitigate outages, the campus owns a diesel generator as a backup system (Figure 3.5b). Own observations indicate that 2-4 power outages occur per month, ranging from ten minutes to over 24 hours. During an outage, the switch to the use of the diesel generator can cause disruptions in the power supply. (Redacted) revealed that a battery plant had previously been installed to neutralize supply fluctuations and outages *“When the power goes out and comes back, it’s a huge surge. It has damaged research equipment before and even broke the backup battery system, which has not been in use since.”* (Appendix E, Interview 3). Currently, the diesel generator remains essential to cover extended outages.

Energy Consumption

Figure 3.6 provides more details on energy usage, based on billing records from the CFE. The Figure shows overall consumption and gives an indication of the capacity needed when implementing new solutions. The energy consumption increases during the summer months. No data is available on the daily usage profile or which areas of the campus are the largest consumers. While exact breakdowns of different types of consumption (for example, research related versus general services) are not available, observations and stakeholder interviews show that a large share of electricity is potentially used for cooling systems, and continuously operating pumps. (Redacted) mentioned: *”In the past, all the air conditioning was centralized, but later they changed to separate units. It’s like switching from two buses to a hundred cars, which of course is far less efficient. We should be more effcient in terms of energy consumption.”* (Appendix E, Interview 1). An overview of availlable data on energy usage is shown in Table 3.1.

When we arrived here, all the air conditioning was centralized, a single machine like in a hotel. But later they changed to 30–40 separate units. It’s like 100 cars polluting much more than two buses; the same happens with energy efficiency.

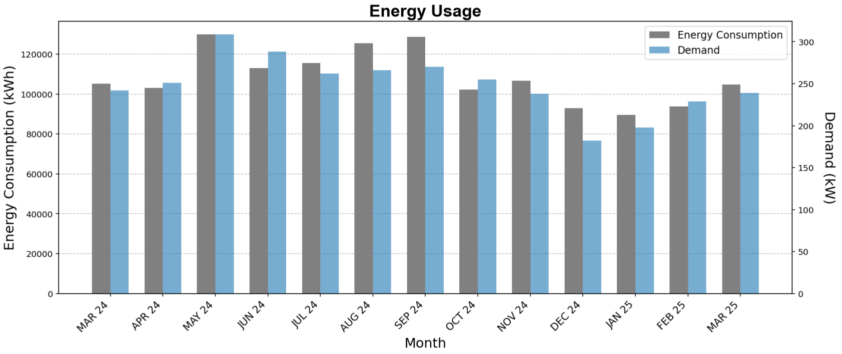


Figure 3.6: Monthly energy consumption and demand of the campus in 2024/2025

Table 3.1: Overview of campus electricity usage

Energy Usage	**Value**	**[Unit]**	**Remarks**
Monthly consumption	115,484	[kWh]	July 2025 selected as 'representative month'
Maximum Demand	309	[kW]	Peak load
Power Factor	98.4	[%]	-
Load Factor	59.2	[%]	-
Average Electricity Price	2.86	[MXN/kWh]	Derived from total energy cost and usage per year
Historical Consumption	80,000–125,000	[kWh/mo]	Seasonal variation
Main Consumers	–	[–]	Cooling systems (A/C) and pumps

There are many gaps remaining in the energy data. These include the lack of historical generator usage, maintenance costs and department-level consumption information. A schematic overview of the energy system is shown in Figure 3.7. A summary of all the known and unknown data is given in Table 3.2.

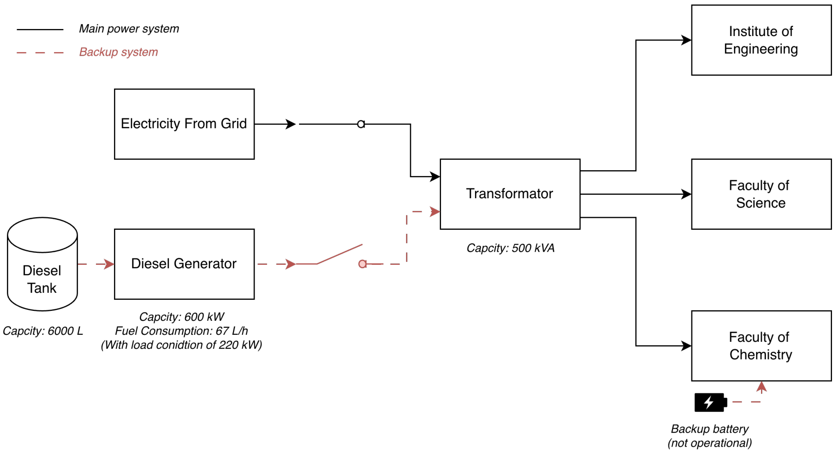


Figure 3.7: Energy system overview

Table 3.2: Known and unknown information for the Energy domain

Known	Unknown
• Diesel generator ≈67 L/h observed during outage (load ≈220 kW). • Generator nameplate: 600 kW; transformer: 500 kVA. • Outages: 2–4/month (10 min to >24 h). • Three recent CFE bills (Apr–Aug 2025): demand [kW], monthly [kWh] (≈80–125 MWh), price. • Normal supply from grid; generator used during outages. • Historical timeseries of wind, solar irradiation, precipitation and temperature available. • Campus power map (feeders, cable routes, panels, protection per building).	• Generator run hours/fuel logs; maintenance costs. • Energy consumption by building/department; major load breakdown (AC, pumps, labs). • Longer demand and energy consumption time-series for trends/peaks. • CO_2 emission data for grid and generator use.

3.4.2. Water

In comparison with the other domains, more information was available on water, due to a study in 2022, carried out by Dr. Juan Manuel Morgan Sagastume, that analysed the current water system at the campus. The wells and dischargers referenced in this paper are mapped in Figure 3.8.

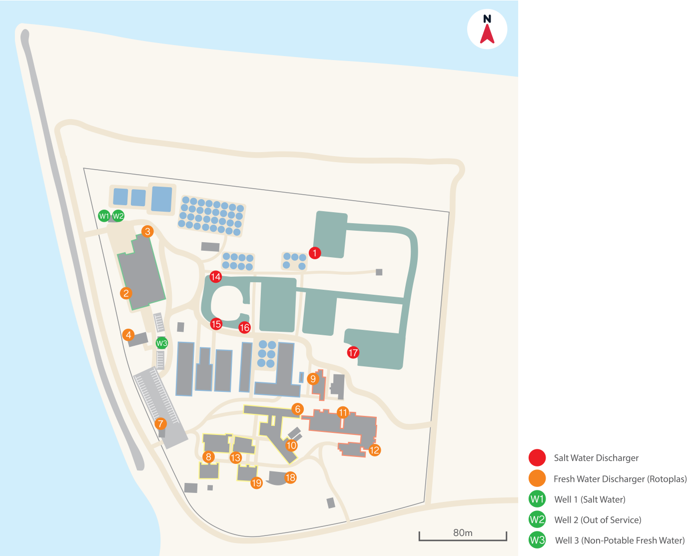


Figure 3.8: Campus water map

By combining the insights from this paper and interviews with the administrative branch of the campus, four water circuits were found, described below.

1. A fresh water circuit that supplies water for general campus use and experiments is extracted from the aquifer through Well 3 (Figure 3.9). This water is distributed to sanitation facilities, the canteen, laboratories, and for cleaning purposes. The water from Well 3 does not meet drinking water standards, and thus cannot be considered potable. Its quality is further challenged by the risk of further salinization (Narvaez-Montoya et al., 2025) and possible contamination from wastewater discharges located upstream of the extraction point (Sagastume, 2022).

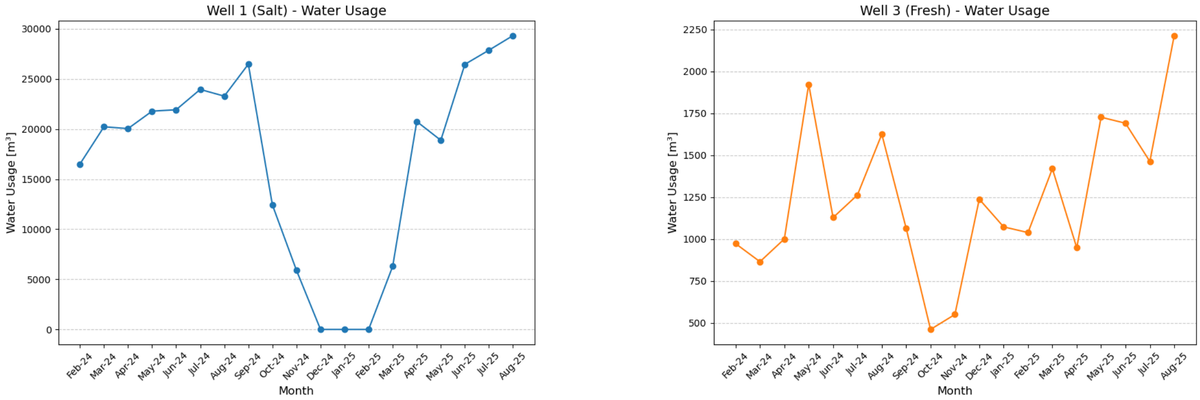
Figure 3.9: The water softener of Well 3 where freshwater is extracted.

2. A wastewater circuit that transports residual water to septic tanks, after which it is discharged back into the aquifer. However, the current septic systems are unable to treat the water in accordance with Mexican water quality standards (NOM-001-SEMARNAT-2021).
3. The delivery of potable water in plastic jugs. There is no fixed infrastructure for drinking water distribution on campus. Approximately one hundred 20-liter containers are delivered each month to cover demand.
4. A saltwater circuit extracted from Well 1 (Figure 3.10) that is used for the aquaculture basins and marine research laboratories. This supply is used for the cultivation and maintenance of marine species, and although the volumes extracted are relatively high, the water is not used for human consumption or sanitation. After use, the saltwater is discharged into designated ponds, ensuring that it does not mix with the campus's wastewater streams (Sagastume, 2022). Since the salt water circuit is treated adequately this circuit will not be further analysed.

Figure 3.10: Pumps of Well 1 that extract saltwater.

Water Consumption

Campus water use is dominated by Well 1 (Figure 3.11a), which supplies the aquaculture basins. As shown in Figure 3.11a, extraction fluctuates strongly: it peaked in mid-2024 at over 30,000 m^3 per month, then dropped to nearly zero between December 2024 and March 2025 when the system was out of service, before recovering in mid-2025.



(a) Well 1: Salt Water Usage

(b) Well 3: Fresh Water Usage

Figure 3.11: Non-potable water extraction.

Furthermore, Sagastume, 2022 reports that in May 2022 an average of approximately 23.9 m^3 of water was extracted daily from Well 3. More recent data (Figure 3.11b) indicate a higher annual daily average of 40.2 m^3, with August 2025 showing the peak extraction of 71.4 m^3 per day. As illustrated in Figure 3.11b, the volume extracted in August was nearly five times greater than that in October (14.9 m^3).

Discharge and Wastewater Management

Saltwater from Well 1 is discharged through points 1, 14, 15, 16, and 17 from ure 3.8, with volumes following extraction trends (Figure 3.12). As it is mainly used in aquaculture, this flow is not considered a major contamination risk.

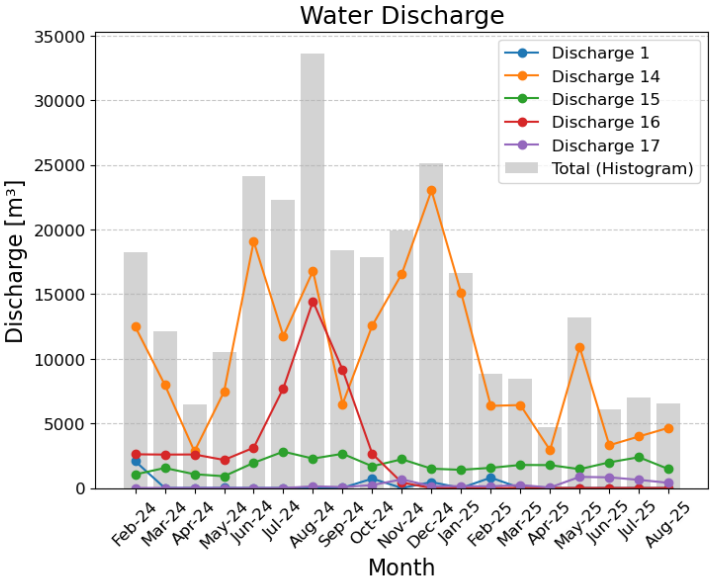


Figure 3.12: Salt Water Discharge

Wastewater sourced from Well 3 are routed into multiple biodigesters, which remove only 40-50% of solids before releasing effluent into the aquifer. The small treatment plant (PTAR), with a capacity of 4 m^3 per day, at the Institute of Engineering has been inactive for years, leaving the campus dependent on these very inadequate systems. Since discharge points lie upstream of Well 3, there is a risk of re-extracting contaminated water. Precise freshwater discharge volumes are not recorded (Sagastume, 2022).

In conclusion, (Sagastume, 2022) already provided several recommendations for future research and implementation based on his analysis:

- Install constructed wetlands in combination with an anaerobic treatment step, a microplant, filtration, and chlorination.
- Develop a future-proof maintenance plan for the installations.
- Conduct a technical–economic feasibility study to identify the most suitable implementation pathway.
- Formulate an integrated plan that encompasses the entire campus rather than focusing solely on the Faculty of Engineering.

The provided recommendations will be used as a starting point for the proposed solutions in the water domain in Chapter 6. As a summary, a system overview of all water circuits is given below (Figure 3.13).

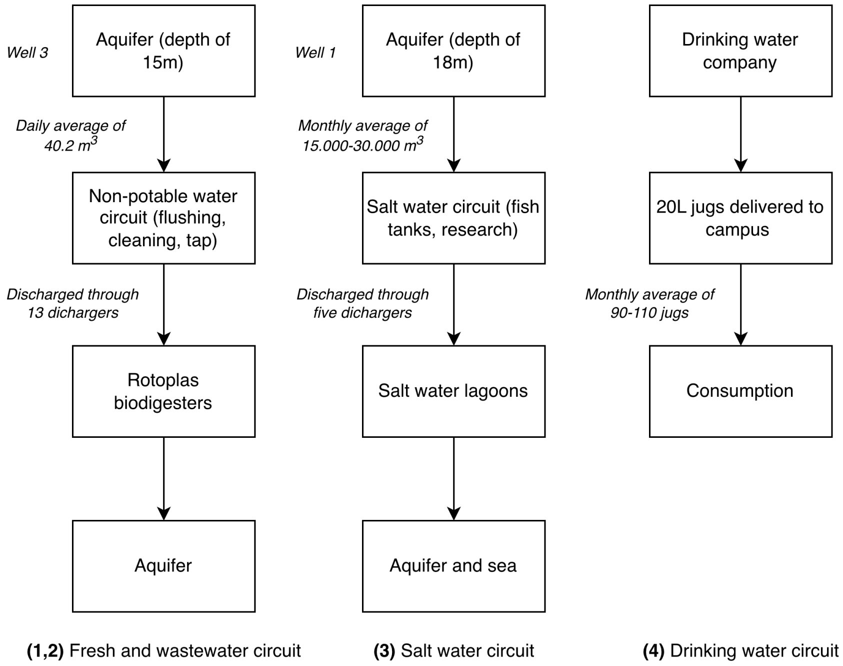


Figure 3.13: Water system overview

Although the study by Sagastume (2022), removed some uncertainties, there still is a significant amount of missing data. A summary of all the known and unknown data is given in Table 3.3.

Table 3.3: Known and unknown information for the Water domain

Known	**Unknown**
• *Salt water*: collected from sea, stored in plastic tanks, used for aquaculture; discharged to salt-water lagoons (also flood control). Monthly volumes tracked since Jan 2024. • *Drinking water*: purchased in 20 L bottles; typical 90–110 bottles/month; invoices available for selected months. • *Sweet/brackish (Well 3)*: supplies sanitation/canteen/labs; not potable; monthly volumes logged since Jan 2024; risks of salinization and upstream contamination noted. • *Harvesting potential*: roof materials, rain data. • Current system filters 40–50% of floating particles. • PTAR at Engineering Faculty: not in use, potential to treat 4 m^3/d and complies with reuse regulations. • Approx. 40.2 m^3/d of freash non-potable water is pumped up of which approx. 23.9 m^3/d is used for use in buildings and approx. 16.3 m^3/d is used for experiments. • Approx. 20 m^3/d of wastewater produced. • First general calculations made for two water management systems.	• Continuous m^3 series for sea intake and lagoon discharge; lagoon flow capacity. • Water use per building or installation • Settling time of dischargers on campus • Tank IDs/locations and service schedule; costs for collection/discharge/maintenance. • Drinking-water delivery/use history • Exact current treatment performance and costs. • CO_2 accounting for water extracting and treatment.

3.4.3. Waste

All campus waste currently falls into two streams: hazardous waste and regular waste. Hazardous waste is handled correctly, by being stored seperately and emptied by a licensed company. All regular waste is collected as a single mixed stream. Indoor bins are emptied into a central container on site, which is reported to be overfull by the time municipal pickup occurs, which on average happens once a month. Some individual bins are seperated into different waste types, yet these are still emptied in the same central container. A small PET-collection cage stands near the entrance (Figure 3.14a), and deposited bottles are taken by the local community of Sisal and sold. According to stakeholder notes, the central container's dimension are 4.5 x 4.0 x 2.5 meters, shown in Figure 3.14b. Although this is a significant capacity, the service frequency still causes the container to be overflowing frequently. Mixed waste is then transported by the municipality to large disposal sites.

(a) PET collection cage at the entrance of the Engineering Faculty **(b)** Garbage collection site.

Figure 3.14: Different waste collection sites at the Sisal campus.

At present, the campus does not measure regular waste quantities or composition. Importantly, the municipal service in Sisal does not (yet) offer separate collection for recyclables, which limits separation efforts on campus. (Redacted) indicated willingness among students and staff to cooperate with separation opportunities: *"Well there is one recycling point for PETS and you can see that it's always full. So people use it. It's not that they won't do it. It's just that we don't give them the option."*. In the system mapping below (see Figure 3.15), an overview can be found of the waste streams.

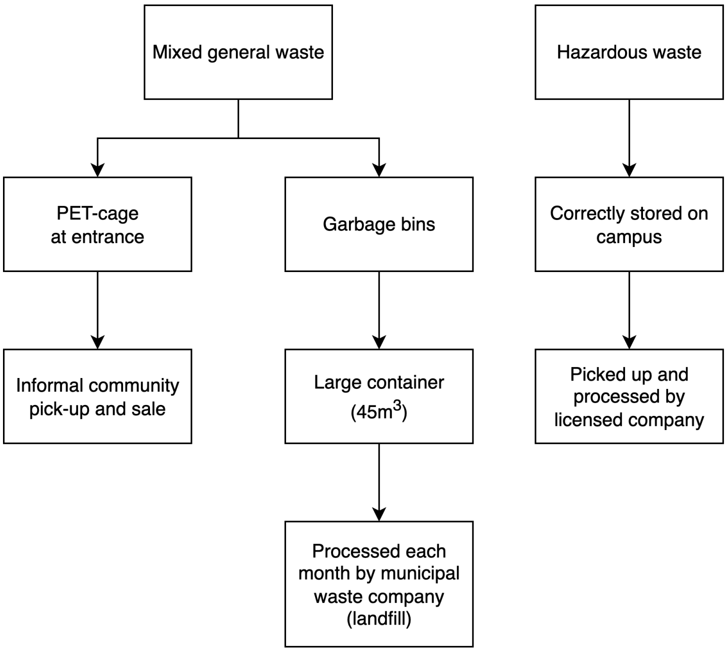


Figure 3.15: System overview of waste streams

A summary of all the known and unknown data is given in Table 3.4.

Table 3.4: Known and unknown information for the Waste domain

Known	Unknown
• General waste currently mixed (no systematic separation). • Small PET cage at entrance; informal community pickup/sale. • Internal bins emptied by concierge to external container. • External container ≈ W4.5 × D4 × H2.5 m; collection ≈ monthly; frequent overflow.	• Quantities by fraction (kg/time); contamination rates; seasonality. • Full bin/container inventory and locations; internal collection routes. • Possible recycling partners and contractual options. • Cost breakdown (collection/hauling/tipping/maintenance). • CO_2 emissions for current logistics and alternatives.

3.4.4. Community and mobility

Besides the main domains of energy, water and waste, other factors influence the current state of the campus. The local community of Sisal, mobility patterns, and connectivity to nearby cities and campuses. Insights from interviews revealed that the relationship between the university and the local community has been complex since the campus was established. As (Redacted) noted, *"Many people don't like the university because they had wrong expectations when it arrived. They thought it would employ half the community. We should work to improve that perception and be more generous."* (Appendix E, Interview 1). Due to time constraints, they are not analysed individually in the remainder of this report. Nevertheless, these findings were considered in the decisions made in the analyses of the main domains of energy, water, and waste.

The link between the Sisal campus and the local community is currently limited. There is modest awareness of campus activities, and the local perceptions around federal land use generate some tension. Communication with the community occurs mainly informally and is not supported by structured events or outreach. This weak connection possibly limits the campus's visibility and its perceived role in Sisal.

The road to Sisal serves as the primary access for staff, students, and visitors, as most of them live in Mérida. Travel times are therefore relatively long: by car it takes approximately one hour to reach Mérida. Public transport options are limited to occasional buses. For almost all users, private cars are the dominant mode of transport. Bicycle use within the village is common, yet road infrastructure towards the campus consists of a sandy road with deep gaps, making it unpleasant for both cycling and driving (Figure 3.16).

Figure 3.16: Road between Sisal and the campus.

Part of this situation, such as the lack of consistent public transport and the roads surrounding the campus, are municipal challenges and, thus, difficult to solve from a campus perspective.

A summary of all the known and unknown data is given in Table 3.5.

Table 3.5: Known and unknown information regarding Mobility and Community

Known	Unknown
• Single road connection to Hunucmá/Mérida; sandy segments with potholes. • Irregular public transport. • Access conditions worsen during heavy rain/storms. • Internal circulation largely unpaved; some ad-hoc bicycle use. • Interaction with town mostly informal; limited structured outreach/events. • Awareness of campus activities among residents appears modest (interviews/observations). • Perceptions around federal land use create some tension.	• Modal split for students/staff; car occupancy; seasonal variation. • Traffic counts at campus gate. • Condition survey and cost responsibility for access road segments. • Willingness to participate; barriers and incentives. • Formal partnerships with municipal services, schools, or local groups.

3.5. Main Findings

The current operational status of the UNAM Sisal campus is characterized by a significant reliance on fragile external systems for energy, water, and waste management, amplified by its coastal location and isolation from Mérida. This dependency creates high vulnerability to environmental stressors like storms and power outages , while internal institutional barriers, such as fragmented governance and limited autonomy, slow down decision-making and hinder local sustainability initiatives. A fundamental challenge across all domains is the absence of reliable operational data, severely limiting effective on-site management and long-term planning for sustainability and self-sufficiency.

- **Energy:** The campus is completely reliant on an unstable national grid supply, leading to frequent outages, which requires the costly and environmentally damaging use of a diesel generator for backup.
- **Water:** Supply is threatened by the salinisation of the local aquifer, while the current wastewater system is inadequate, with effluent failing to meet Mexican quality standards and risking contamination of the groundwater. Potable water must be delivered in plastic jugs from Mérida.
- **Waste:** All regular waste is collected as a single mixed stream in a container that frequently overflows, with no systematic separation, composting, or recycling in place, leading to local pollution.
- **General:** Decision-making is slowed by a dual governance structure (academic and operational) and dependence on the central authority in Mexico City , while the campus's remoteness causes resource dependency and vulnerability to extreme weather events like storms and flooding.

4

Future vision

As mentioned in Chapter 2, the creation of a future vision of the UNAM campus in Sisal is step 2 of the backcasting method. This step defines the desired long-term outcome, which will later be used in Steps 3 and 4 to work backward and identify the technological, cultural, and institutional changes required to achieve it (Quist et al., 2006b). Stakeholder perspectives obtained from the interviews and surveys will be analysed. These insights will be combined with existing sustainability goals to create the future vision. At the end, the set goals will be benchmarked with other sustainability initiatives.

4.1. Perspective of campus community

Since the university campus involves many layers of staff and students, it is essential to include these groups early in the process to manage long-term and complex challenges such as sustainability (Antunes et al., 2006). To frame the future vision, we used the input of these core stakeholders based on findings from interviews and surveys (see appendix E and H).

4.1.1. Staff perspectives

During the interviews with the staff, the focus was on their vision on sustainability, and their prioritisation of the three main domains: energy, water and waste. Energy was mainly related to the unstable supply and inefficient use of equipment such as air conditioning. Water was discussed in relation to the function and salinity of the wells, wastewater treatment, and the efficiency of the existing infrastructure on campus. Waste management was described as fragmented and lacking a simple overarching strategy across the campus. The staff also raised issues related to mobility and connectivity to Mérida, as well as the campus's relationship with the local community. These were considered important contextual factors but fall beyond the primary scope of the future vision, as mentioned in the previous chapter.

4.1.2. Student perspectives

As described in Chapter 2, a survey was conducted to gain insight into the student perspectives (see appendix H). Students most often mentioned energy reliability as a priority, pointing to outages as disruptive for study and daily life. Waste management was also seen as problematic, with calls for clearer waste separation systems and more visible initiatives, especially since this was seen as an easy-to-tackle challenge. Water was acknowledged as important, though less frequently mentioned compared to staff. Beyond these three domains, students also highlighted other aspects of daily campus life, such as the need for shared spaces designated for leisure or sport, simple food options, and improved transportation to and from Mérida. A number of students felt that participation in sustainability initiatives is currently limited, due to weak communication and the lack of visible projects.

4.1.3. Synthesis

The interviews show that staff value self-sufficiency and sustainability and tend to focus on infrastructure, resilience, and long-term autonomy. Students emphasized daily reliability, visibility, and engagement. Both groups highlight the value of linking the campus to the local community, with students already proposing possible projects to engage Sisal in sustainability-related events or projects.

Interviewees also mentioned administrative hurdles within UNAM as barriers to implementing sustainability related projects, which was confirmed by (Redacted): *"I sent a plan to the central administration about sustainability and nobody said anything, it didn't exist."* (Appendix E, Interview 1). While these challenges are real, they aren't included in the future vision, as UNAM's organizational structure is too large and complex to address from this campus level. The developed future vision concentrates on the domains of energy, waste, water, while also taking into account potential economical, local or community-related constraints.

4.2. Future vision

Building on the insights from the interviews in Chapter 3 and aligned with UNAM's institutional sustainability goals (López, 2024), the future vision focuses on achieving resource self-sufficiency, implementing visible circular practices, and ensuring regulatory compliance.

4.2.1. Energy

By 2035, the Sisal campus mainly runs on renewable sources, with a diesel generator only in place as a backup for emergencies. Energy systems are designed to be resilient to outages caused by storms or grid failures, which was emphasised by university staff in Chapter 3. Efficiency is achieved both through centralized and optimized systems and through staff and student awareness, reducing unnecessary consumption.

- 1a. 90% of the campus energy comes from renewable sources.
- 1b. Energy consumption is reduced by 30% compared to 2035.
- 1c. Backup systems are in place for critical research facilities, ensuring continuity during outages.

4.2.2. Water

Water management on campus prioritizes both sustainable sourcing and discharges according to the standards and requirements of the Mexican government. By diversifying supply and treatment methods, dependency on external sources is reduced and environmental pressure is minimised.

- 2a. At least 50% of fresh water comes from local, sustainable sources.
- 2b. 100% of wastewater is treated
- 2c. All discharged wastewater complies with government regulations, protecting local ecosystems.

4.2.3. Waste

Waste management is integrated into campus life, with clear separation systems and links to regional circular economy initiatives. Awareness is present among staff, students, and the community, creating the opportunity to operate as an example, demonstrating how academic institutions can reduce landfill dependency and stimulate local recycling industries.

- 3a. Waste is separated into different streams, with all streams collected and processed by partner companies.
- 3b. Composting is applied for organic waste.
- 3c. Circular economy practices are established in collaboration with local cooperatives and recycling companies.

4.3. Justification of targets

The targets need to be both ambitious and realistic. This section will therefore explain the reasoning behind the quantitative targets discussed in section 4.2. Each goal is supported by examples from other universities, literature, or specific conditions of the Sisal campus. In addition, the goals are consistent with the UNAM institutional sustainability strategy (López, 2024).

4.3.1. Energy targets

A lot of universities worldwide have committed to running on 100% renewable energy or achieving carbon neutrality by 2030-2035. Examples include Aalto University and Wageningen University, both aiming for carbon neutralility by 2030 (Aalto University, 2024; Wageningen University & Research, 2024). At a smaller scale, the Southwestern University in Texas, consisting of only 1434 students, has sourced 100% renewable energy since 2010 (Southwestern University, 2019).

While it is difficult for the UNAM campus in Sisal to reach 100%, for example due to its reliance on a diesel generator for emergencies and possible financial constraints, achieving $>$90% renewable energy is within reach, especially given Yucatán's strong solar and wind potential (Canul-Reyes et al., 2025; Figueroa-Espinoza et al., 2014).

The interviews revealed baseline inefficiencies on the Sisal campus, such as the reliance on multiple small AC units and pumps running continuously throughout the day (Appendix E). These conditions suggest that achieving a 30% reduction in energy consumption is not only realistic but potentially more attainable here than on already optimized campuses. Comparable cases, such as UC Merced, have demonstrated reductions of around 30% through retrofits and system upgrades, showing that similar measures could deliver substantial improvements at Sisal as well (Mercado et al., 2013).

4.3.2. Water targets

For the UNAM campus, overall reductions in water demand are difficult to achieve due to research activities requiring large quantities of water. Therefore, the focus is more on the treatment of wastewater and innovative solutions to source water locally. As shown in a sewage plan for a campus in Ecuador, where they managed to treat their waste water adequately (Merchán-Sanmartín et al., 2022).

4.3.3. Waste targets

A basic example of a potential improvement in waste programs is the the elimination of single-use plastics, as UCLA has done (University of California, Los Angeles, 2023). While the reduction of single-use plastics was mentioned by both students and staff, we have found that these plastics are still used around the campus. Larger universities, such as Cornell, show programs in composting and recyling, allowing for inspiration on how to tackle waste in a sustainable way (Cornell University, 2025).

In addition, many universities have zero-waste goals. The University of California integrates diversion targets, recycling programs and upstream reduction policies into its framework towards zero-waste (University of California, 2025). While the UNAM's university-wide goals are less ambitious, only focussing on the reduction of solid waste (López, 2024) an increased focus on zero-waste is realistic and achievable.

Finally, the integration with regional recycling companies is important as well. Due to Sisal's relatively small volume of waste, it might not be feasible to build full treatment capacity on campus. These collaborations also align with circular economy principles, ensuring that waste is treated as a resource rather than a disposal problem.

5
Energy

This chapter focuses on the energy system of the campus. As discussed in Chapter 3, the current energy supply relies on two main sources: the electricity grid and a diesel generator used during power outages. Due to limited data on specific energy consumption and hourly variations per department, it is not yet possible to perform a thorough analysis of energy efficiency or storage options, which are necessary when considering renewable energy. Therefore, this chapter focuses specifically on opportunities for sustainable energy generation on campus.

These solutions are in line with goal 1a, to supply 90% of the campus energy from renewable sources. The recommendations also consider to reduce energy use by 30% (goal 1b) and ensure backup systems for critical facilities (goal 1c), although these last two are not analysed in depth.

Within the field of sustainable energy generation, various technologies exist, including solar, wind, biomass, geothermal, and tidal systems (International Energy Agency, 2023). However, solar and wind contain the best data in terms of available local measurements. This made them more suitable for further analysis. Moreover, both represent the most feasible and scalable renewable options for a remote coastal campus such as Sisal. As described in Chapter 2, reanalysis was used to supplement the available on-site measurements, making them suitable for assessing the solar and wind potential at the campus. Both energy sources are compared through a Multi-Criteria Analysis (MCA), and recommendations are given for their future implementation at UNAM Sisal.

5.1. Possible solutions: Energy Resources

1: Solar

Photovoltaic (PV) panels convert sunlight into electricity using semiconductor cells (International Energy Agency, 2023). The focus of this study is not to identify the best solar panel on the market, but rather to estimate the possible contribution of solar energy to the campus energy supply to reach the goals set in Chapter 4. To make this estimate, several assumptions and simplifications were made. An explanation of how reanalysis radiation data was scaled to create a usable dataset for estimating solar energy potential can be found in Appendix B.1.

For the estimation of the potential of solar energy production, the following assumptions were made:

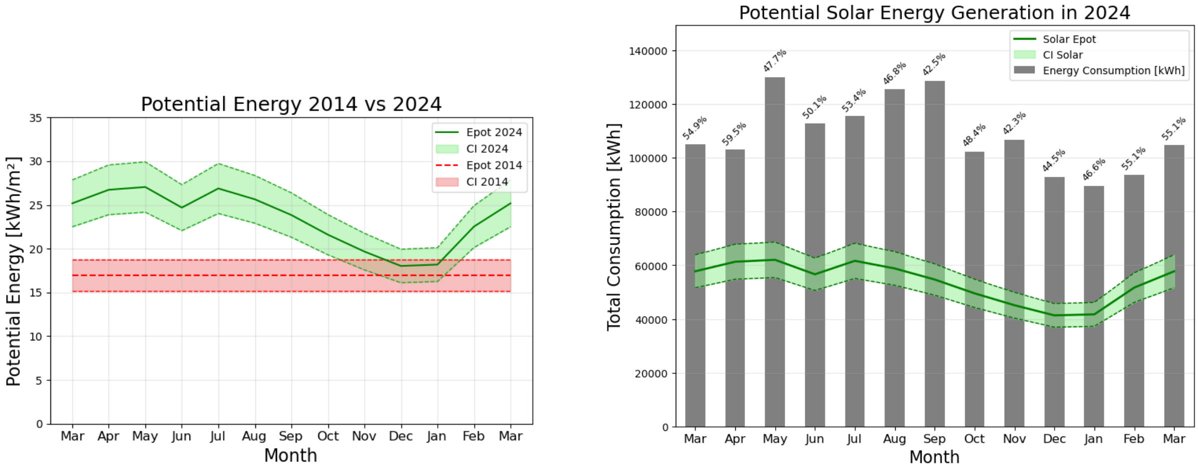
1. The ERA5-2SQM mean monthly solar radiation (Figure B.4) resembles the mean monthly solar radiation from Figure 6a of the paper from Morcillo-Herrera et al. (2014). Therefore the potential Annual Energy Yield (AEY) of Sisal and Mérida are assumed equal.
2. The paper from Morcillo-Herrera et al., 2014 reports a single AEY [$\mathrm{kWh\,m^{-2}}$] throughout the year. This value is adjusted for each month based on the monthly solar radiation distribution in Sisal. For this adjustment a 10-year (2014-2024) ERA5-2SQM data set is used. For clarification, see Appendix B.2.
3. Since the paper mentioned above is from 2014, the values should also be adjusted for efficiency improvements on PV technology. PV efficiency is assumed to have increased from 16% (circa 2014) to 22% today (+37.5%) (Philipps & Warmuth, 2025).
4. An overview of the available surface for solar panels is summarised in Figure 5.1 and Table 5.1. It is estimated that 60% of this area can be used due to structural limitations, shaded areas and air conditioning units on the roofs. This value is estimated based on conversations during a visit from Premier Solar to the campus. This yields 2 292 $\mathrm{m^2}$ of installable area.
5. The maximum expected wind speed with a 100-year return period is 31 m/s (see Figure C.13). It is assumed the roofs/solar panels can withstand the forces exerted by this wind speed. This assumption is based on consultations with experts from Premier Solar.

Figure 5.1: Potential surface area of solar panels based on Google Earth.

Table 5.1: Available surface area per location

Location	Area [m^2]
Faculty of Engineering (Green)	455
Faculty of Science (Yellow)	1308
Faculty of Chemistry (Red)	940
Parking (Black)	1118
Total	**3821**

With these assumptions, a estimate for the solar energy potential can be calculated. Assumptions 2 & 3 are visualised in Figure 5.2a. Multiplying these values by the available surface area shows that the potential solar energy share in Sisal's energy system ranges from 42.3% to 59.5%, depending on the time of year (Figure 5.2). The detailed steps for this analysis can be found in Appendix B.2.



(a) Efficiency improvement 2014-2024

(b) Potential Solar Energy Yield

Figure 5.2: Potential Solar Energy overview

2: Wind

Wind velocities in Sisal are significantly higher than in nearby locations on the Yucatan Peninsula. The dominant winds come from the northeast and southeast. The wind follows a seasonal pattern that shows violent winds from winter cold fronts, while during the summer rainy season the average wind speeds decrease. The most powerful winds are associated with tropical storms and hurricanes (Figueroa-Espinoza et al., 2014).

The study by Figueroa-Espinoza et al. (2014) analysed the wind regime at Sisal using measurements from a 50 m meteorological mast. The results revealed a bimodal distribution at low altitudes, caused by alternating land and sea breezes. At higher elevations, the wind field becomes more uniform, resulting in a unimodal pattern and higher wind power density. This implies that near-surface wind at the UNAM Sisal campus is highly variable and dominated by low-speed regimes, whereas consistent energy potential is found at higher altitudes. For small-scale applications for the Sisal campus, this suggests prioritising turbines with low cut-in speeds and good performance under variable, turbulent conditions.

The wind conditions at the UNAM Sisal campus were further analysed using data from the ERA5-2SQM dataset. For clarification, see Appendix C.1. This dataset results in the Probability Density Function (PDF) and windrose from Figures 5.3 and 5.4, respectively. The PDF shows a slight kink around 7 m/s. This feature is consistent with alternating land- and sea-breeze from Figueroa-Espinoza et al. (2014). The wind-speed distribution can be interpreted as a mixture (superposition) of two Weibull components, one associated with land breezes and one with sea breezes. The intersection of these two components occurs near 7 m/s and produces the observed kink. Similarly, Figure 5.4 shows that the predominant wind directions are from the northeast and southeast, matching the bimodal pattern previously observed for the Yucatán coast.

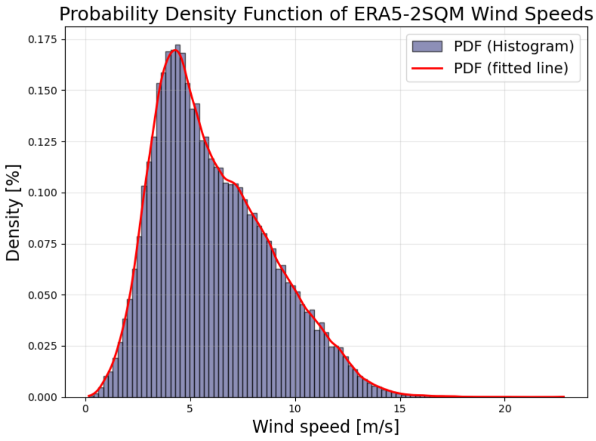


Figure 5.3: Probability Density Function of ERA5-2SQM wind speeds (2000-2025)

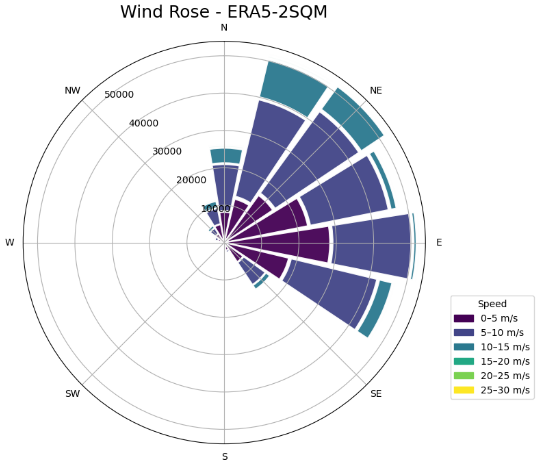


Figure 5.4: Windrose from ERA5-2SQM dataset

Wind power density increases at higher elevations. However, large-scale wind turbines are economically unfeasible for this study and are therefore not considered. Instead, small-scale horizontal and vertical axis wind turbines designed for urban environments are evaluated based on the study performed by Krehenbrink (2024). The Aelos-V 5000W turbine from that study was selected to perform a representative case study. It was chosen for its low cut-in wind speed, power output, compact size and costs, which make it suitable for use on the campus. The parameters of this turbine are shown in Table 5.2. The probability density and cumulative distributions (PDF above and ECDF shown in Appendix C.1) confirmed that most wind speeds at hub height range between 3 m/s and 10 m/s, corresponding well with the operating range of small-scale turbines. This supports the selection of low cut-in speed designs for the Sisal context.

Table 5.2: Overview of parameters for the Aelos-V 5000W vertical axis wind turbine.

Parameter	Value	[Unit]
Rated Power	5	[kW]
Cut-in speed	2.5	[m/s]
Cut-out speed	16	[m/s]
Survival speed	52.2	[m/s]
Rotor diameter	4.5	[m]
Noise emissions	45	[dB(A)]
Warranty	5	[years]

The maximum wind speed with a return period of hundred years is 31 m/s. This if based on the Extreme Values Analyses in Appendix C.2. This indicates a low structural risk for small-scale turbines such as the Aelos-V 5000W, which has a survival speed of 52.2 m/s (Krehenbrink, 2024).

The values in Table 5.2 are used to calculate the wind potential. For this estimation, a setup of five Aelos-V 5000W wind turbines was selected, corresponding to an approximate total footprint of 100 m^2.

Although additional turbines could technically be installed, this number was considered a realistic starting point. With five turbines, negative effects such as noise disturbance, bird interactions, and reduced efficiency due to wake effects are limited. With this setup the negative effects can be assessed, and the setup could be expanded when favourable. Further details of this analysis can be found in Appendix C.3.

Figure 5.5 shows that wind energy has a significantly smaller potential contribution compared to solar energy, assuming the installation of five turbines. The estimated contribution of wind power to the campus energy demand ranges between 4.1% and 10.9%, depending on seasonal wind variations.

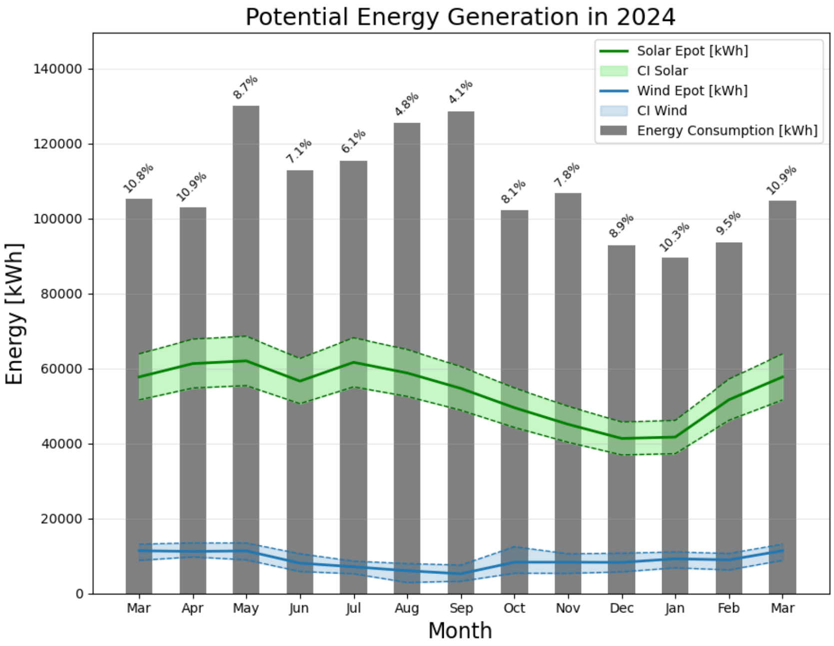


Figure 5.5: Potential wind energy compared to solar energy.

Cost overview possible solutions: Energy Resources

Table 5.3 presents estimates of cost variables of implementing photovoltaic (PV) panels and small-scale wind turbines to assess the feasibility of both options. The underlying assumptions and calculations supporting these results are detailed in Appendix D.1. These values will be used to compare the two resources in the MCA in the following subchapter.

Table 5.3: Comparison of calculated performance indicators for the two energy resources. (Sol. 1: Solar energy, Sol. 2: Wind energy)

Criteria	**[Unit]**	**Sol. 1**	**Sol. 2**
CAPEX	[USD]	(Redacted)	112,168
OPEX	[USD/year]	18,019	5608
Life Cycle	[year]	30	20
Potential Yield	[kWh/year]	642,129	103,441
Electricity price	[USD/kWh]	0.10	0.11
Needed Surface Area	[m^2]	2,292	100
ROI	[%]	612	168
Payback period	[years]	7	10

3: Microgrids and Smart Energy Systems

Microgrids present an integrated approach to improving the stability and reliability of local energy systems, especially when renewable energy sources such as solar and wind are introduced. A microgrid is a localized network that can operate independently or in coordination with the main grid, integrating multiple distributed generation sources (DGs), energy storage, and local consumption (Hossain et al., 2019). Such systems can increase energy resilience, reduce dependency on external power supply, and optimize the balance between generation and demand.

A relevant example for the Sisal context is the microgrid implemented at the University of Puerto Rico at Mayagüez, which successfully combines renewable energy sources and storage to maintain operation during hurricanes and grid outages (Garcia et al., 2022). This demonstrates that microgrids can be highly effective for institutions located in hurricane-prone or remote areas.

Microgrids represent an integrated framework that combines energy generation, storage, and management. Since the analysis of energy storage and consumption could not be performed due to missing data, the implementation of a microgrid system at UNAM Sisal also cannot be quantitatively assessed. Therefore, this concept is not evaluated in the MCA but is acknowledged as a long-term opportunity once sufficient data and infrastructure become available.

5.2. MCA: Energy Resources

To evaluate potential energy solutions for the UNAM Sisal campus, a Multi-Critical Analysis (MCA) was conducted, as described in the methodology. The specific reasoning behind each grade per solution can be found in Appendix D.2. The results are presented in Table 5.4.

Table 5.4: Multi-criteria evaluation of two energy solutions for the Sisal campus. *Sol. 1 = Solar Energy ; Sol. 2 = Wind Energy*

Criterion	Weight	Sol. 1	Sol. 2
How much investment is needed to implement this solution? (Capex)	4.4	5	7
How expensive is it to operate and maintain the system? (Opex)	4.6	7	8
What is the expected lifetime of the solution before replacement?	4.2	9	7
Can the solution withstand extreme weather conditions common in Sisal?	4.8	9	8
Can the solution withstand (extreme) floodings common in Sisal?	3.8	10	10
How reliable is the solution during power outages?	5	9	9
How much (renewable) energy can the solution generate?	3.8	8	3
What is the expected CO_2 reduction compared to current emissions?	2.4	8	5
How much land or space does the solution require on campus?	2.6	5	7
Does the solution risk harming or benefit the local ecosystem (e.g. mangroves, biodiversity)?	3.2	8	6
How complex is the operation of the solution (installation, monitoring, etc.)?	4	7	8
How likely are the students and staff of the campus to accept and use this solution?	4	7	5
Does the solution actively involve the benefit of local community?	4	6	2
Total score		**386.4**	**339.2**
Normalized score		**7.61**	**6.68**

The results of the MCA show that solar energy performs better overall than wind energy for the UNAM Sisal campus. This is primarily because of its much higher energy yield, which could cover up to half of the campus's total electricity demand compared to only 4–10% for wind. Consequently, solar energy offers greater potential for CO_2 reduction and therefore contributes more to the long-term goal of of supplying 90% of the campus's total energy demand from renewable sources. While solar panels require a higher initial investment and regular cleaning due to dust and salt exposure, they have a significantly longer lifespan and, having no moving parts, lower operational risks compared to wind turbines. These characteristics make solar energy a more reliable and sustainable long-term option.

Wind energy scores slightly higher in terms of investment cost and space requirements, as small-scale turbines are relatively affordable and require limited rooftop area. However, their low generation capacity means that many additional units would be needed to achieve an output comparable to solar power, which would raise costs and increase visual and noise impacts. Large-scale deployment could therefore affect the visual quality of the campus and potentially local tourism. Solar installations are easier to scale, less visually intrusive, and more suitable for community participation. For instance, through shared installations on residential or public buildings in Sisal. Overall, they represent the most practical and inclusive renewable energy solution for the campus, while small-scale wind turbines could serve as a complementary technology in the future.

5.3. Recommendations

Following the analysis of the solar and wind energy potentials and the results of the MCA, it becomes clear that both resources can play a role in the campus's transition toward a more sustainable and resilient energy system. Looking at the future vision goals defined for 2035, reaching 90% renewable energy supply on campus will be challenging under current conditions. Based on the estimated potentials, solar and wind combined could cover around 60% of the energy demand of the Sisal campus. However, implementing both systems at full capacity is unlikely to be financially or technically realistic in the short term. Since solar energy shows the highest potential and scalability, it is recommended to prioritize this technology as the foundation of the campus's renewable energy transition. Wind energy may be considered as a complementary source in later stages, especially for distributed or backup generation.

Achieving the 90% target will also depend on reducing total energy consumption through improved efficiency and monitoring. Therefore, a crucial first step is to gather detailed energy data. With this data, energy use can be optimized, making the 90% renewable target more feasible. In the longer term, the integration of smart or microgrid systems could allow the campus to operate independently, further improving resilience and sustainability. The following recommendations present a phased approach outlining the actions for the short, medium, and long term.

Short-term (0–2 years)

- **Measurements:** The lack of data can be addressed by installing energy meters in each department. All types of energy usage should be mapped, distinguishing between research and general services. Load profiles should be recorded daily, weekly, and monthly for at least 12 months. By comparing demand with on-site generation, the size of storage needs and power outage frequency and duration can be identified.
- **Awareness:** Start with introducing simple norms, such as maximum AC temperature, doors and windows closed, lights and equipment off when leaving the campus.
- **Solar PV initiation:** Start the project of implementing solar panels by opening a tender. Simultaneously start permitting and procurement requests. Discuss possible new agreements with the net provider and define a monitoring and maintenance strategy.
- **Wind feasibility:** Run a small-scale wind turbine pre-study (permits, bird/ecology impact, visual/noise assessment, community acceptance) to inform a go/no-go.

Midterm (2–5 years)

- **Energy reduction:** Using the collected data from major energy consumers, start a study for optimization of these systems.
- **Integrated solar energy:** The PV-solution should be fully integrated, scaled to a production of minimal 50% of the energy consumption.
- **Storage & control:** Based on the measured load profiles, develop a storage and energy regulation strategy. Start by looking at integration of storage for critical labs.
- **Wind decision:** Decide on small-scale wind (install pilot or drop); if "no", reallocate budget to additional PV or Storage solutions.

Long-term (5–10 years)

- **Implement micro/smart grid:** Start feasibility project on island-mode capabilities and investigate smart grid infrastructure possibilities.
- **Community involvement:** Share renewable energy production knowledge to the community.
- **Optimization and scaling:**Evaluate system performance against the 90% renewable energy target. If not reached, optimize high-consumption systems based on the performed mid-term study and expand the generation capacity.

6

Water

This chapter focuses on the harvesting of water and the treatment of wastewater. As defined in the future vision in Chapter 4, water is identified as one of the key pillars in achieving a more sustainable Sisal campus. As mentioned in the current situation the watersystem can be divided into 4 subsystems. This report will focus on subsystems 1, 2 and 3.

At present, all drinking water is supplied from Mérida, making the campus highly dependent on external resources and contributing to transport-related emissions. In addition, all freshwater used as greywater is extracted from the local aquifer, which is contaminated. Producing freshwater on-site could therefore reduce CO_2 emissions from transportation, lower costs, decrease dependency on external sources, relieve pressure on the aquifer, improve water quality, and minimize waste. Consequently, Goal 2a aims for 50% of the campus's freshwater demand to be met locally.

At the same time, the current system for wastewater handling is inadequate. Wastewater is discharged without proper treatment. With improved infrastructure, this water could be treated and safely returned to the aquifer and improving environmental performance. Consequently, a target has been set to treat 100% of campus wastewater (goal 2b) and comply with quality norms (goal 2c).

In this chapter, subsystems 1,3 (water harvesting) and subsystem 4 (water treatment) are addressed separately. For each, a literature review has been conducted and interviews have been carried out to identify possible solutions. Since a first assessment of subsystems 1 and 2 was already undertaken by (Sagastume, 2022), these plans are incorporated and integrated into this report. The identified solutions are then analysed and evaluated in the context of the Sisal campus with a MCA. Furthermore, experts were consulted to discuss implementation and feasibility. Finally, all this information will be integrated into recommendations for the short, mid and longterm to create a roadmap in Chapter 8.

6.1. Possible Solutions: Water Harvesting

1: AC Condensate Harvesting

Air conditioning systems operating in hot and humid environments produce significant volumes of condensate water. According to Okeyinka et al., 2021 this reclaimed condensate typically contains very low levels of contaminants and is chemically similar to distilled water. However, it may exhibit slightly acidic pH values and can include trace metals such as copper or zinc, often originating from corroded cooling coils. Although suitable for nonpotable purposes by default, with minor treatment, such as pH neutralization using calcite or magnesium oxide filters, AC condensate can be upgraded for potable use.

Given that there is a large quantity of air conditioning on the Sisal campus, particularly in laboratory buildings, AC condensate represents a low-cost and low-energy supplementary water source. Although its yield may not meet the total demand, it could help to reach goal 2a, especially during peak cooling periods.

2: Small-Scale Desalination

Desalination technologies offer the ability to produce potable water from brackish groundwater or seawater, both of which are readily available at the Sisal site. Kariman et al., 2023 present a comprehensive overview of small-scale desalination systems, including reverse osmosis (RO), membrane distillation, and humidification-dehumidification technologies. These systems have been increasingly applied in off-grid remote and rural contexts.

A pilot project described by Tigrine et al., 2016 demonstrates the successful operation of a solar-powered RO system designed for both brackish and seawater sources. The system delivered potable water while operating efficiently under variable solar energy input, illustrating its potential for sites with intermittent electricity supply, such as the Sisal campus, which currently relies on diesel generators. Additionally, this system could be integrated with the campus's solar PV infrastructure, allowing it to operate during periods of overproduction and thereby enhancing energy circularity. Furthermore, the system showed promising performance in terms of both energy consumption and water quality, suggesting that a similar installation could be adapted for the campus's needs.

The type of installation described by Tigrine et al., 2016 is comparable to the solutions offered by Elemental Water Makers (EWM). For this project, the founder of EWM was consulted and interviewed to discuss the potential challenges identified earlier. EWM can deliver a plug-and-play desalination system (Figure 6.1) that, according to the company, is technically feasible for the Sisal campus. The company has experience implementing similar systems in coastal regions worldwide, including Mexico and the Caribbean. In addition to providing the technology itself, EWM offers training for operation and maintenance, which supports long-term system performance and success. Moreover, their systems can be integrated with other elements of this plan, such as the utilization of surplus solar energy. Lastly, EWM provided a preliminary cost overview of a potential installation at the campus to support the estimation of CAPEX and OPEX for the MCA.

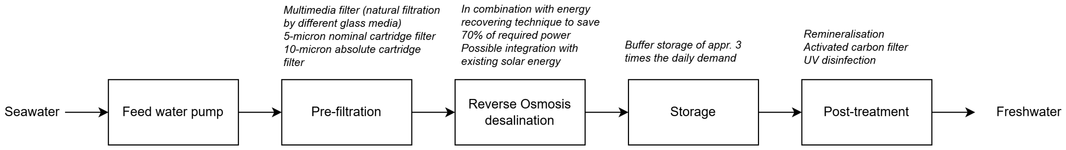


Figure 6.1: Elemental Water Makers Desalination Solution

3: Rainwater Harvesting

Rainwater harvesting (RWH) is another relevant approach that leverages natural precipitation to reduce potable water demand. Delibaş Mısırlı and Şişman, 2024 applied the Rational Method to estimate harvestable volumes on a university campus, considering surfaces such as rooftops, hardscapes, and landscaped areas. Their findings indicated a potential to harvest nearly 300 million liters per year (five times the campus's annual water consumption) demonstrating the substantial potential of RWH for campuses in climates with seasonal rainfall.

In addition, Rodrigues et al., 2023 advocate for integrated systems that combine RWH with greywater reuse. Their review highlights the benefits of such systems in urban areas, particularly in improving water self-sufficiency and reducing pressure on local aquifers. The implementation of these systems is especially relevant for the Sisal campus, where fresh water is currently delivered by truck from Mérida and is pumped up from the aquifer, creating logistical and environmental pressure.

Rainwater harvesting aligns well with the campus's goal for increased self-sufficiency and sustainability. However, these systems require adequate storage, filtration, and management to ensure water quality and continuous supply during dry periods.

Cost overview possible solutions: Water harvesting

To allow for comparison and to be able to fill in the MCA in next section, for all solutions the CAPEX, OPEX, Life Cycle, Potential Yield and Needed Surface Area were calculated and shown in Table 6.1. These calculations are rough estimates and can be found in Appendix F.1.1. The lifecycle of each solution is defined by the expected lifetime of its key component, which represents the most critical element of the installation.

The calculations of solution 1 and 3 are based on simple systems designed and installed under favourable conditions. Consequently, the absolute values should not be overinterpreted; they are best used as relative indicators and as a first approximation of each solution's potential. While the installations may appear to deliver drinking-water quality in principle, achieving consistent potability in practice is considerably more challenging. We therefore assume that additional upgrades would be required to meet regulatory standards, and that, at this stage, the most appropriate application of the produced water is for greywater uses. Furthermore, the calculations for solution 2 are based on data provided by Elemental Water Makers (EWM), which are confidential. Therefore, the detailed calculations cannot be disclosed.

The numbers were shared for internal use only and are excluded from this report for open access, as permission for public publication was not granted.

Table 6.1: Comparison of calculated performance indicators for the three Water Harvesting solutions. (Sol. 1: AC Condensate Harvesting, Sol. 2: Small-Scale Desalination, Sol. 3: Rainwater Harvesting)

Criteria	[Unit]	Sol. 1	Sol. 2	Sol. 3
CAPEX	[USD]	10.6k	(Redacted)	23.5k
OPEX	[USD/year]	640	13k	1k
Life Cycle	[year]	15	25	20
Potential Yield	[m^3/day]	0.18	44	5.92
Needed Surface Area	[m^2]	1.62	6	6.1k

6.2. MCA: Water Harvesting

To evaluate the potential water harvesting solutions for the UNAM Sisal campus, a Multi-Criteria Analysis (MCA) was conducted as described in Chapter 2. The graded scores are based on literature in which the solution is proposed. The specific reasoning behind each grade per solution can be found in Appendix F.1.2. The weights are determined by a survey completed by relevant stakeholders. The results are presented in Table 6.4.

Table 6.2: Multi-criteria evaluation of three water harvesting solutions for Sisal campus

Question	Weight	Sol. 1	Sol. 2	Sol. 3
How much investment is needed to implement this solution? (Capex)	3.8	9	5	8
How expensive is it to operate and maintain the system? (Opex)	4.3	9	5	8
What is the expected lifetime of the solution?	4.3	6	8	7
How much water does the solution yield?	3.8	5	9	7
How much land or space does the solution require on campus?	2.3	9	7	4
Can the solution withstand extreme weather conditions common in Sisal?	4.3	7	8	6
Can the solution withstand (extreme) floodings common in Sisal?	4.5	7	7	5
Can the solution maintain functionality during periods of drought?	4.0	8	9	3
How well does the solution cope with high salinity levels in water sources?	4.8	10	9	5
How much energy does the solution consume during operation?	3.8	9	3	8
What is the expected CO_2 reduction compared to the current water system?	2.8	6	9	8
How well does the solution ensure the quality of the water?	4.5	7	9	6
Does the solution risk harming or benefit the local ecosystem?	5.0	7	6	8
How complex is the operation of the solution?	3.3	8	6	7
How likely are the students and staff of the campus to accept and use this solution?	4.0	8	6	8
Does the solution actively involve the benefit of local community?	4.5	6	7	8
Total score		**482.9**	**449.9**	**425.9**
Normalized score		**7.5**	**7.0**	**6.7**

Solution 1 (AC Condensate Harvesting) achieved the highest score (7.5). This solution performs well in terms of cost-effectiveness, simplicity, and energy efficiency. With low capital and operational costs, it represents an immediately feasible and low-impact measure that can be implemented with minimal disruption to the existing infrastructure. Moreover, it consumes almost no additional energy, as it uses condensate produced by existing air conditioning systems. Its small needed surface area and independence from groundwater salinity make it particularly suitable for the Sisal campus.

However, its main limitation lies in its small yield and strong dependency on air conditioning use. Potential periods of low occupancy, limit its contribution to total water demand (40.2 m^3/day vs 0.18 m^3/day). On the other hand, it could potentially cover the drinking water demand (0.07 m^3/day) if water quality is carefully monitored, as there remains a risk of contamination by metals and acidic residues. It scores high in environmental criteria since no water from the local environment is subtracted. Furthermore, if applied for drinking water, it can reduce plastic waste and reduce CO_2 emissions by eliminating truck transportation. In conclusion, it serves as a practical entry-level solution that increases sustainability awareness and demonstrates visible on-site water circularity.

Solution 2 (Desalination) follows with score of 7.0. Its main advantages are reliability and scalability. It offers a technically robust and independent water source, capable of producing a consistent and reliable quality of water from seawater, which can also be used for drinking purposes with proper certification and monitoring. It ensures supply during droughts and could cover the entire fresh water demand of the campus. If the installation is powered by solar energy, it provides a water production system that does not emit CO_2. On the other hand, during periods of low energy consumption and high solar production it can be used to buffer water and contribute to energy efficiency.

Despite these advantages, desalination has the highest capital and operational costs among the three options and requires technical expertise for maintenance. However, this problem could be mitigated by Elemental Water Makers (EWM) because they offer training and assistance with the installation. Furthermore, energy requirements and brine disposal to the local environment present additional challenges in the local context. The system's investment costs makes it less suitable for immediate implementation and acceptation but highly relevant as a medium/long-term solution, once local capacity and funding are secured.

Solution 3 (Rainwater Harvesting) closely follows with a score of 6.7 but excels in complementary areas such as water circularity and ecosystem compatibility. It has a relatively low CAPEX and OPEX in relation to its potential yield, which makes it a promising option. The system can cover a significant portion of water demand (15%) and provides clear environmental benefits by reducing runoff from buildings. However, sufficient storage capacity is required to account for the variability of seasonal rainfall.

Furthermore, the solution can contribute to CO_2 reduction, as less groundwater needs to be pumped, and it could potentially be used for drinking water. However, rainwater quality is not always consistent, as contamination from debris, bird droppings, and sea spray on rooftop surfaces may occur, which results in a lower score for water quality. Furthermore, due to its visibility and easily understandable technology, the level of acceptance is high. In addition, its ease of implementation and quick results make it suitable for involving the local community and sharing tangible benefits. In conclusion, rainwater harvesting could be a short-,mid- and long-term strategy that can be combined with other systems to improve water autonomy and can be used for knowledge sharing.

6.3. Possible Solutions: Water Treatment

1: Centralized Subsurface Constructed Wetland

Within this solution, all wastewater from the campus would be collected and treated in one central plant. The system includes a small pumping and screening unit, followed by an anaerobic tank that removes most solids and organic matter. The partially treated water then flows through a planted, gravel-filled wetland built above ground and fully lined to protect it from flooding and groundwater infiltration. Within the wetland, natural biological and filtration processes further reduce pollutants. The flow of this system is illustrated in, which shows the main treatment steps and the movement of water through the installation. The conceptual flow of this system is illustrated in Figure 6.2, which shows the main treatment steps and the movement of water through the installation. If water reuse is desired, a filtration and disinfection step can be added at the end of the process.

The existing septic tanks on campus would continue to serve as pretreatment, reducing the solids load before water enters the new wetland. This setup builds directly on the proposal by UNAM engineers in 2022, who recommended a campus-wide treatment system using anaerobic pre-treatment and subsurface wetlands to meet regulatory standards. Their report highlighted the need for above-grade, lined systems due to Sisal's high groundwater table and frequent flooding (Sagastume, 2022).

Similar systems have shown strong results in tropical coastal regions. For example, Pérez-Salazar et al. (2019) reported stable organic matter and pathogen removal in small-scale "biogarden" wetlands along the Pacific coast of Costa Rica, even under variable seasonal conditions. These findings confirm that low-energy wetland technologies can achieve reliable performance in humid coastal environments comparable to Sisal.

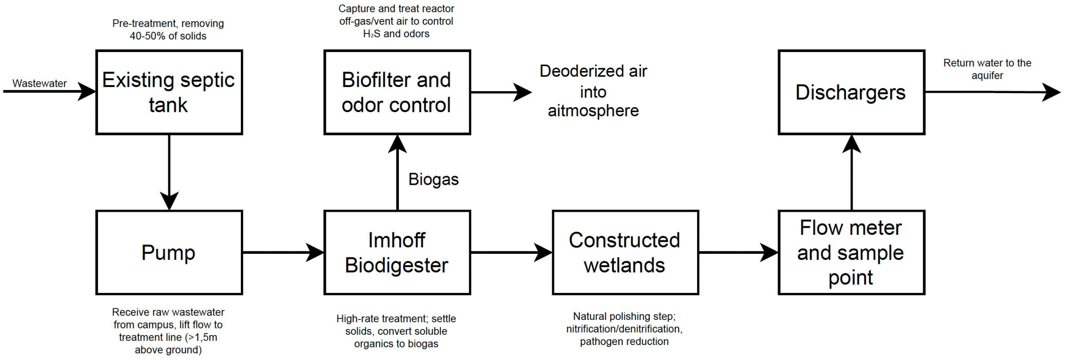


Figure 6.2: Flowchart Subsurface Constructed Wetland

2: Decentralized Subsurface Constructed Wetland

This alternative uses the same process as the centralized option but divides the wetland into 3-4 smaller wetland units located near different building clusters. Each cluster includes its own small wetland and primary treatment tank, built on raised and lined pads to prevent flooding and infiltration. The current septic tanks would again function as pretreatment, stabilizing the flow and reducing solids before the wetland stage.

This approach is in line with the modular treatment concept introduced by Sagastume (2022), which proposed the use of small, locally managed units to handle wastewater from separate campus zones. Their study described a similar setup at the II-UNAM building (combining septic tanks, filtration, and optional disinfection) to comply with regulations. Building on this concept, decentralized wetlands would allow a phased rollout, starting with the largest building clusters and expanding over time.

Such decentralized systems are particularly suited to flood-prone coastal campuses, where redundancy and flexibility are key. Despite the overall higher cost, the scalability and resilience of this decentralized alternative could make this approach a practical fit for the campus' spatial layout and operational capacity.

3: Moving Bed Biofilm Reactor

In a Moving Bed Biofilm Reactor (MBBR), wastewater is pumped into a compact bioreactor where biological treatment occurs on carrier media (small plastic elements) that remain suspended in the reactor and provide a large surface area for biofilm to grow. As the wastewater flows through, the microorganisms in the biofilm degrade organic matter and nitrogen compounds, in a continuous, low-maintenance process. The system doesn't require the cycle control or sludge-handling complexity of SBRs, making it robust and easier to automate (Ødegaard, 1998).

The BIOBOX Organic Matter system is a plug-and-play example of a Moving Bed Biofilm Reactor (MBBR), in which wastewater flows through a compact bioreactor filled with carrier media that support biofilm growth. As illustrated in Figure 6.3, the biofilm degrades organic compounds under anoxic conditions using nitrates as an electron acceptor, producing clean effluent with a low biochemical oxygen demand (the amount of dissolved oxygen needed by microbes to break down the organic matter) and no nitrates. The modular design allows for easy installation, low maintenance, and reliable compliance with regulatory discharge standards. This technology is already applied in small communities and campuses in regions such as Spain, Morocco, and Vietnam for the treatment of domestic and light industrial wastewater (BIOBOX Water, 2023).

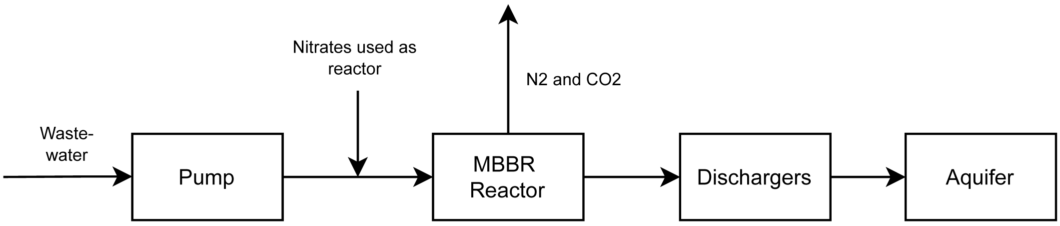


Figure 6.3: Flowchart MBBR

Cost overview possible solutions: Water treatment
The following table summarises the financial and operational performance indicators of the 3 water treatment solotions. The full calculation process and underlying assumptions can be found in Appendix F.2.1.

Table 6.3: Comparison of calculated performance indicators for the three Water Treatment solutions. (Sol. 1: Centralized SCW, Sol. 2: Decentralized SCW, Sol. 3: MBBR)

Criteria	[Unit]	Sol. 1	Sol. 2	Sol. 3
CAPEX	[USD]	113k	163k	115k
OPEX	[USD/year]	9.03k	16.3k	2.19k
Life Cycle	[year]	25	25	25
Capacity	[m^3/day]	20	20	20
Needed Surface Area	[m^2]	155	3x55	14.8

6.4. MCA: Water Treatment

To evaluate the potential water treatment solutions for the UNAM Sisal campus, a Multi-Criteria Analysis (MCA) was conducted as described in the methodology. The specific reasoning behind each grade per solution can be found in Appendix F.2.2. Based on the scores the solutions with the highest potential will be further evaluated for the Sisal campus. The results are presented in the Table 6.4.

Table 6.4: Multi-criteria evaluation of three drinking water solutions for Sisal campus

Question	Weight	Sol. 1	Sol. 2	Sol. 3
How much investment is needed to implement this solution? (Capex)	3.8	7	6	7
How expensive is it to operate and maintain the system? (Opex)	4.3	6	5	8
What is the expected lifetime of the solution?	4.3	7	7	7
Can the solution withstand extreme weather conditions common in Sisal?	4.3	6	6	9
Can the solution withstand (extreme) floodings common in Sisal?	4.5	6	6	8
How much energy does the solution consume during operation?	3.8	8	8	6
What is the expected CO_2 reduction compared to the current water system?	2.8	6	6	6
To what extent can the solution reuse water on campus?	4.5	6	6	8
How well does the solution ensure the quality of the water?	4.5	7	7	8
How much water does the solution treat?	3.8	6	6	8
How much land or space does the solution require on campus?	2.3	3	4	9
Does the solution risk harming or benefit the local ecosystem (e.g. mangroves, biodiversity)?	5.0	8	8	9
How complex is the operation of the solution (installation, monitoring, etc.)?	3.3	7	6	8
How likely are the students and staff of the campus to accept and use this solution?	4.0	6	6	8
Does the solution actively involve the benefit of local community?	4.5	5	5	5
Total score		**380.3**	**371.2**	**454.4**
Normalized score		**6.4**	**6.2**	**7.6**

Solution 1 (Centralized Subsurface Constructed Wetland) has a score of (6.4) and offers a low-energy and ecologically integrated approach, capable of treating the entire wastewater volume of the campus in a single facility. Its main advantages lie in its low OPEX, proven reliability, and compatibility with

natural treatment principles. This system requires minimal external inputs and contributes positively to biodiversity if landscaped properly. However, its large spatial footprint and the need to construct it above ground level to avoid flooding make it less feasible. Maintenance of vegetation and sludge removal demand moderate human capacity, which could challenge long-term operation if resources are scarce.
In a future scenario where campus population and water discharge increase moderately, this option remains viable and scalable by adding an extra cell to the wetland. Yet, under extreme weather scenarios or if sea-level further rise, the vulnerability to flooding and saline intrusion makes the centralized system less resilient.

Solution 2 (Decentralized Subsurface Constructed Wetland) scores lowest (6.2). This option divides treatment into several smaller systems (3–4 units), each serving a cluster of buildings. This layout enhances resilience, as individual failure does not compromise the whole treatment chain. It also allows phased implementation, starting with the largest clusters such as the Institute of Engineering. These strengths make it attractive in the short term, particularly if investment capacity is limited or if new buildings are added gradually. However, decentralization increases both CAPEX and OPEX due to duplication of pumping, lining, and maintenance infrastructure. Coordinating multiple units also demands more operational oversight.
This solution performs better in long-term adaptation scenarios. If the campus expands or the discharge points are relocated, additional wetlands can be integrated modularly. Nevertheless, in high-flood conditions, protection measures must be applied individually at each site, increasing complexity.

Solution 3 (Moving Bed Biofilm Reactor) stands out with a 7.6 for its compact design, automation, and robust treatment quality. The system performs well even under fluctuating loads, producing effluent that complies with regulatory standards. Its low operational costs, small footprint, and ease of relocation make it ideal for a campus with limited space and exposure to floods. Furthermore, its modular configuration enables capacity expansion if water use increases in the future. The main drawbacks are the higher electricity demand and dependency on technical components, which require periodic inspection and replacement. These factors make it slightly more complex to maintain compared to wetlands, yet still within feasible limits if the staff receives training.
In future scenarios of higher automation and renewable energy integration, such as with the proposed solar PV system, the MBBR aligns perfectly: its energy needs can be met with on-site renewables. In addition, its enclosed setup avoids odor and mosquito issues, increasing user acceptance.

6.5. Recommendations

In the short term, the focus should be on low-cost pilot projects, data collection, and preparatory steps that build a stronger evidence base for larger interventions. Implementing small-scale rainwater harvesting and AC-condensate collection pilots provides immediate results while testing assumptions. These pilots could potentially cover part of the drinking water demand and simultaneously raise awareness among staff and students about on-site circularity.

Parallel to this, establishing a systematic and continuous water quality monitoring program is essential. Monthly sampling of wells, inlets, and discharges will create a reliable dataset to finalize the design of the proposed solutions. At the same time, flow meters should be installed at key distribution outlets and dischargers to map water flows across buildings and equipment, allowing identification of the campus's primary water users. This information is currently missing but crucial for scaling up future systems such as a small-scale desalination plant.

Using this data, short-term improvements can already be made to the existing septic tanks by optimizing desludging schedules and checking the integrity of pipes and tanks. This reduces overflow risk and improves baseline effluent quality while new treatment options are being prepared. Securing the necessary permits for seawater extraction and discharge should also be prioritized, as this will be a prerequisite for any future desalination.

Finally, the campus should begin preparing the institutional and financial conditions for investment. This includes drafting funding proposals for a modular MBBR and a desalination system. Early engagement with suppliers and the UNAM board can shorten lead times and create momentum. In parallel, defining clear maintenance responsibilities and checklists will help ensure that even small pilots are properly managed, setting the example and prepare for later stages.

In the mid term, the focus shifts from piloting and data collection toward the implementation of full-scale systems that build upon gained experience from earlier efforts. Based on the results of the short-term pilots, the campus can move forward with the installation of a modular MBBR unit to treat all wastewater produced on-site, ensuring compliance with regulatory standards.

At the same time, the small-scale desalination system can be installed and, if installed, integrated with the existing solar PV infrastructure. This allows the system to operate primarily on renewable energy. This small-scale desalination plant could potentially cover all fresh-water demand. With extra monitoring and certification efforts, this desalination plant could also cover the total drinking water demand for the campus. In parallel with the installation of large-scale systems, the distribution infrastructure should be modernised to prevent contamination and leakage of freshwater within the network.

Rainwater harvesting and AC-condensate systems can now be expanded to additional buildings using the performance data from the pilots, while water monitoring and maintenance routines become embedded in campus operations. Together, these steps establish a functioning circular water system and a solid operational framework that can be scaled up in the long term.

In the long term, the campus should transition towards a fully integrated and self-sufficient water system that minimizes dependence on the aquifer and external supply while ensuring compliance with environmental standards. By combining the desalination plant with the MBBR treatment unit and the rainwater and condensate harvesting systems, the campus can achieve a self-sufficient and sustainable water cycle, meeting way over 70% of its total demand from locally produced freshwater.

The desalination system will become the primary source of fresh and potable water for the campus, utilizing the readily available seawater along the coast. Rainwater and AC-condensate harvesting will complement this system by providing additional supply during the rainy and humid seasons, increasing overall water security. Beyond their technical function, these visible and easily implemented measures can act as demonstration projects for local residents and organizations, showcasing practical examples of sustainable water management in coastal environments. Meanwhile, the MBBR installation will continue to treat all wastewater prior to discharge, ensuring compliance with regulatory standards and protecting the quality of the underlying aquifer.

Finally, maintaining a structured monitoring and maintenance program will be crucial to safeguard water quality and long-term performance. With these systems in place, the Sisal campus can serve as a regional model for sustainable coastal water management, demonstrating how academic institutions can combine technological reliability with environmental responsibility in a challenging coastal setting.

From the text the following actions are recommended to guide the short-, mid-, and long-term implementation of water harvesting and treatment solutions at the Sisal campus:

Short-term (0–2 years)

- **Rainwater harvesting and AC-condensate pilots:** Install small storage tanks connected to roofs and air-conditioning units to measure actual yields and quality.
- **Water quality monitoring program:** Establish monthly sampling of wells, inlets, and discharges to create a continuous dataset.
- **Flow monitoring and sub-metering:** Install flow meters at key outlets and dischargers to map distribution and identify major water users.
- **Septic system improvements:** Optimize desludging schedules and inspect pipes and tanks for leakage or blockages.
- **Permitting:** Apply for seawater extraction and discharge permits with the relevant authorities.
- **Funding preparation:** Develop investment proposals for a modular MBBR and small-scale desalination system; engage with suppliers and the UNAM board.
- **Maintenance planning:** Define maintenance responsibilities and checklists for pilots and existing systems.

Mid-term (2–5 years)

- **MBBR installation:** Construct and commission a modular wastewater treatment unit to handle all campus discharge.
- **Desalination plant implementation:** Install a small-scale solar-powered desalination system to meet total freshwater demand.
- **Expansion of harvesting systems:** Extend rainwater and AC-condensate collection to additional buildings using pilot data.
- **Infrastructure modernization:** Upgrade and expand internal water distribution to prevent contamination and losses during storage and transport.
- **Integration into operations:** Embed water monitoring and maintenance routines within regular campus management.

Long-term (5-10 years)

- **Integrated campus water system:** Combine desalination, wastewater treatment, and harvesting systems to achieve a self-sufficient and resilient water cycle.
- **Desalination as main source:** Operate the desalination plant as the primary provider of fresh and potable water, supported by rainwater and condensate harvesting.
- **Maintenance and monitoring framework:** Institutionalize long-term maintenance responsibilities, performance tracking, and quality control.
- **Regional collaboration and knowledge sharing:** Position Sisal as a demonstration site for sustainable coastal water management.

7

Waste

The UNAM Sisal campus currently disposes all of the waste in a single 45 m^3 container, which is collected roughly once a month. There is no systematic separation, composting, or recycling in place. The aim for the campus is to develop a more structured and circular waste management system that can be locally operated and maintained.

To work towards the future vision goals mentioned in chapter 4.2.3, several interviews and literature reviews were carried out to find waste management approaches that fit the specific context of Sisal. The most promising solutions are analysed and compared in this chapter using a Multi-Criteria Analysis (MCA), which looks at both technical and organisational feasibility as well as environmental and social impacts.

Before selecting and analysing the different solutions, it is important to define what steps are needed first to manage waste effectively on the campus. Based on an interview with Francisco Alfaro, representative of the *Secretaría de Desarrollo Sustentable* (State Office for Environmental Sustainability) of Yucatán, the first step is to measure and characterise the waste that the campus produces. This includes determining how much waste is generated and what types of materials it contains. Such a study should follow the official Mexican standards: NMX-AA-061 (generation study), NMX-AA-015 (quartering method for representative sampling), NMX-AA-022 (physical composition), and NMX-AA-019 (volumetric weight determination). This baseline data is necessary to define the next steps and plan future actions effectively.

Once this is known, the next focus can be on implementing short- and medium-term organisational measures. In the longer term, technical solutions could also be considered once the necessary infrastructure and experience are in place. The following section explores these organisational and technical options based on literature and insights from interviews.

7.1. Possible Solutions: Waste

1: Zero waste grassroots programme

One promising organisational model is the Zero Waste Program (ZWP). This program relies on community-led, bottom-up action rather than being a university policy imposed from above. The program operates through a collaboration with a local non-governmental organization (NGO) that pick ups the seperated waste and treats it properly. This creates a shared learning structure. The program provides a closed waste management cycle by covering on-campus separation and collection, temporary storage, and coordinated recycling or disposal through a partner NGO. The multi-bin separation system is an important operational element of this program. This system provides the separation of PET, paper, glass, aluminium, and organic waste. To ensure proper treatment and recycling of the materials, partnerships with local NGOs or recycling companies are essential. The programme represents a low-cost and proven model that has already been successfully implemented within another UNAM campus, making it suitable for replication at the Sisal campus (Jiménez-Martínez & García-Barrios, 2020).

The main limitations of the ZWP are its reliance on local participation and external partners. At the Cuernavaca campus, the NGO We Recycle was responsible for transporting, storing, and selling recyclable materials. Since no such organisation currently operates in Sisal, this could pose a challenge if no reliable partner can be found. The program also depends on continuous awareness and active engagement from students and staff, who must correctly separate their waste and use the designated bins. Without institutional support and coordination, participation may decrease over time. Long-term success therefore requires both active community involvement and formal commitment from the university.

2: Integral Solid Waste Management Program

The Integral Solid Waste Management Program (ISWMP), described by Oyama et al. (2018), takes a more formal, top-down approach compared to the community-based ZWP. Instead of being led by students or staff, it is organised through university policies and coordinated by the campus administration. The program manages both organic and inorganic waste through a structured system. This system includes on-site composting, collaboration with external institutions for green waste treatment and organised collection of recyclables such as PET, aluminium, paper, and batteries. With its clear monitoring and measurable results, the ISWMP demonstrates how a university campus like Sisal could formalise community-based waste efforts into a consistent and well-managed system.

The main limitation of the ISWMP is that it depends on internal leadership and funding. Although the program has worked well at the Cuernavaca campus, many UNAM sustainability initiatives remain isolated to single campuses or rely on the commitment of a few motivated individuals (Oyama et al., 2018). Without long-term institutional support or a university-wide strategy, such programmes can lose momentum once leadership roles change. For the Sisal campus, this means that the success of the ISWMP would depend on clear integration with UNAM's broader sustainability goals and on establishing a management structure that can keep the program running over time.

3: Community-Based Social Marketing (CBSM)

The Community-Based Social Marketing (CBSM) approach aims to change behaviour and increase participation rather than building large-scale infrastructure. It focuses on the individual and community level by identifying and removing practical barriers that prevent people from acting sustainably. At the UABC Ensenada Campus, for example, CBSM was used to set up a successful paper and cardboard separation program. The main barrier identified was inconvenience, so students designed a simple system with extra bins placed in offices and corridors. They collected the materials themselves, after which a recycling company came to pick them up. This bottom-up approach made participation easy and effective (Vega et al., 2010). For Sisal, a similar method could serve as a low-cost first step to raise awareness and encourage engagement before developing a full waste management system.

However, the program's success strongly depends on the availability of students to carry out the collection. At UABC, the amount of collected waste dropped during holidays and semester breaks, showing that the system is vulnerable when students are not present. This dependence would need to be managed carefully to ensure the continuity of the program. In addition, the program did not use financial incentives, which might limit motivation for some individuals (Vega et al., 2010).

4: Waste Plastic Pyrolysis Oil Technology

As described by Park et al. (2024), pyrolysis is a thermal process that converts plastic waste into a liquid fuel known as pyrolysis oil. This is done by heating the plastic to high temperatures (around 400–600°C) without oxygen. This prevents burning and instead breaks the plastic down into smaller hydrocarbon molecules that can be reused as an energy source. The process also produces by-products such as gases and char, some of which can be reused to power the system itself.

A study at a mid-sized university campus in South Korea assessed the potential of installing a small on-site pyrolysis plant. The results showed significant greenhouse gas reductions and a possible annual economic benefit of about 350,000 USD compared to landfill or incineration (Park et al., 2024). Although the study was based on a more urban and industrially connected campus than Sisal, it suggests that decentralised pyrolysis systems could help remote campuses manage non-recyclable plastics while generating a usable energy product.

However, the technology is still in an early development stage. There are uncertainties regarding costs, efficiency, and technical reliability. Pyrolysis can also emit pollutants such as nitrogen oxides (NOx), requiring expensive cleaning equipment to meet regulations. Moreover, the system has high upfront costs that were not included in the original study, which could make it less feasible without external funding (Park et al., 2024).

5: Anaerobic Digestion (AD)

Anaerobic digestion (AD) is a biological process in which microorganisms break down organic material, such as food waste, in the absence of oxygen. This produces two useful products: biogas, a renewable energy source, and digest, which can be used as fertilizer. A 240-day study at a university in Brazil tested a semi-pilot biodigester using food waste from a campus restaurant. The system achieved a 95% reduction in pollutants and produced biogas with around 60% methane. This shows strong potential for treating organic waste in small, decentralized settings like Sisal (Granzotto et al., 2021).

However, AD is a complex biological process that is sensitive to factors such as pH, temperature, and the composition of the input material. Variations in food waste can disrupt the process and reduce methane production. In addition, other challenges include high investment and operating costs. This may limit feasibility without sufficient funding or technical support (Granzotto et al., 2021).

7.2. MCA: Waste

It is important to note that the estimation of costs and lifespans (CAPEX, OPEX, and life cycle) for the evaluated waste management solutions is highly uncertain. The reviewed literature does not provide consistent or detailed financial data, as the case studies differ widely in nature and scope: from non-commercial, community-driven initiatives to early-stage industrial technologies. As a result, direct quantitative comparison is difficult, and the analysis presented here should be interpreted as indicative rather than absolute.

For the organizational and behavioural solutions (Solutions 1, 2 and 3), the available studies emphasize social innovation, institutional engagement, and low-cost participation rather than economic efficiency. These programs often depend on voluntary labour, NGO partnerships, and simple infrastructure such as bins and composting areas. Consequently, their success and longevity depend more on community participation and institutional continuity rather than on financial return or efficiency.

For the technological options (Solutions 4 and 5), the challenge is different. Pyrolysis and Anaerobic Digestion (AD) are emerging technologies with high capital requirements and complex operational demands (Minz et al., 2025). The available economic data for the pyrolysis case study explicitly excluded CAPEX figures due to uncertainty, while the AD study reports only energy outputs, not investment or maintenance costs. In addition, the lack of quantitative data on the current waste composition and generation rates at the Sisal campus makes it impossible to perform precise potentials, cost-benefit or payback analyses.

Despite these limitations, conducting a Multi-Criteria Analysis (MCA) remains valuable because it provides a structured framework to compare qualitatively different solutions on a common basis. Even when precise cost data are lacking, the MCA enables a systematic assessment of technical feasibility, environmental impact, social acceptance, and organizational fit using available literature and contextual estimates. Rather than providing exact financial outcomes, the MCA highlights the relative strengths and weaknesses of each solution and identifies which strategies are most suitable for further development at the Sisal campus. The specific reasoning for each grade per solution can be found in Appendix G. The results are presented in Table 7.1.

Table 7.1: Multi-criteria evaluation of five waste management solutions for the Sisal campus.
Sol. 1 = Zero Waste Grassroots Programme ; Sol. 2 = Integral Solid Waste Management Program; Sol. 3 = Community-Based Social Marketing (CBSM); Sol. 4 = Waste Plastic Pyrolysis Oil Technology; Sol. 5 = Anaerobic Digestion (AD).

Criterion	**Weight**	**Sol. 1**	**Sol. 2**	**Sol. 3**	**Sol. 4**	**Sol. 5**
How much investment is needed to implement this solution? (Capex)	4.0	9	7	9	3	5
How expensive is it to operate and maintain the system? (Opex)	3.4	8	6	8	3	6
What is the expected lifetime of the solution before replacement?	4.2	8	9	6	8	7
Can the solution withstand extreme weather conditions common in Sisal?	3.2	9	8	9	9	9
Can the solution withstand (extreme) floodings common in Sisal?	4.4	9	8	9	7	8
To what extent does the solution promote circularity (reuse, recycling, closed loops)?	4.0	7	8	8	8	8
How much can the solution reduce local/regional pollution?	4.6	9	8	8	7	7
How effectively does the solution divert waste from landfills or incineration?	4.4	8	8	7	7	8
What is the expected CO_2 reduction compared to current waste handling practices?	3.2	7	7	7	5	8
How much land or space does the solution require on campus?	2.8	9	7	9	6	8
Does the solution risk harming or benefit the local ecosystem (e.g. mangroves, biodiversity)?	4.8	9	8	8	7	7
How complex is the operation of the solution (installation, monitoring, etc.)?	4.2	6	5	5	3	4
How likely are the students and staff of the campus to accept and use this solution?	4.2	9	7	9	3	6
Does the solution actively involve / benefit the local community?	4.2	9	2	3	5	3
Total score		**461.4**	**390.2**	**413.8**	**323.0**	**369.4**
Normalized score		**8.30**	**7.02**	**7.44**	**5.81**	**6.64**

The results of the Multi-Criteria Analysis (Table 7.1) show a clear difference between organizational and technological waste solutions. Overall, the organizational and behavioural solutions (Solutions 1–3) perform better than the technological options (Solutions 4 and 5). This can be explained by their low financial costs and by the fact that they are more likely to be accepted and supported by the campus community. This makes them particularly suitable for short-term implementation at the Sisal campus.

Solution 1 (Zero Waste Grassroots Programme + multi-bin system) achieved the highest overall score (8.30). It combines a proven, low-cost model with strong social engagement. Because it has already been implemented at another UNAM campus, it provides a realistic and scalable example for Sisal. Its strong performance across nearly all criteria reflects its integrated approach: waste separation, raising awareness, and building partnerships with local recycling actors. The main risk lies in its dependency on continuous participation of students and staff and reliable partnerships with recycling companies, which are essential for long-term success.

Solution 3 (Community-Based Social Marketing) follows closely (7.44) but scores slightly lower due to its operational limitations. The approach relies heavily on student participation for col vvlection and coordination, which can be challenging during semester breaks or periods of low engagement. This dependence is reflected in its lower operational score. In addition, the system is only suitable for campus-level application, as it is not realistic for students to handle waste collection in the wider community. However, CBSM offers a practical and low-cost starting point for improving awareness and separation habits among students and staff, laying the groundwork for more structured systems like the Zero Waste Program.

Solution 2 (Integral Solid Waste Management Program) performs slightly lower (7.02). This is mainly because of its higher costs, (even) higher complexity, and limited external community benefit. The higher costs are due to the additional infrastructure required. While the program's on-campus composting and multi-stream collection improve circularity and reduce landfill waste, it mainly focuses on internal university operations. If expanded to include cooperation with local recycling companies or municipal services, it could have a stronger social and regional impact. This makes it a promising medium-term option once the basic waste management system is in place.

In contrast, the technological options (Solutions 4 and 5) score lower overall, reflecting their high CAPEX/ OPEX and greater operational complexity. Waste plastic pyrolysis (Solution 4) ranks the lowest (5.81) because it is capital intensive, focusses only on plastic waste, and requires trained staff and pollution control systems. It remains a long-term possibility, but only if funding and technical capacity increase. Anaerobic Digestion (Solution 5) performs slightly better (6.64) and offers stronger environmental benefits, such as CO_2 savings and closed-loop reuse of organic waste, but it still requires continuous monitoring and a stable feedstock supply. These technologies could become realistic future options once the campus has established a stable waste management system with consistent separation practices and operational capacity.

7.3. Recommendations

Following the analysis of the current situation and the results of the Multi-Criteria Analysis (MCA), it is clear that the UNAM Sisal campus currently lacks any formal waste management system. All waste is collected in a single mixed stream and transported to municipal disposal sites without separation, recycling, or monitoring. The first and essential step is therefore to quantify and characterize the campus's waste streams according to the official NMX standards. This baseline will identify the most relevant waste streams for separation and guide future collection and treatment strategies. Once this data is available, the campus can re-engage with the State Office for Environmental Sustainability, which has expressed willingness to support implementation.

In the short term, the campus should focus on low-cost, organizational solutions. The Zero Waste Grassroots Programme (Solution 1) offers the most suitable starting point, combining waste separation, composting, and awareness. If implementation proves challenging, a simplified approach inspired by Community-Based Social Marketing (Solution 3) could be used to build engagement among students and staff. Establishing partnerships with NGOs or recycling companies will be essential to ensure that seperated materials are properly collected and processed.

Once the waste management framework operates successfully within the campus, it could be gradually expanded to the broader community of Sisal, improving cooperation between the university and local stakeholders. This would not only increase recycling rates but also enhance social engagement and improve the relationship with the local community. Once the system operates effectively, it could be expanded to include the local community, improving recycling rates and fostering a stronger connection between the campus and the community.

In the longer term, once the organizational framework and infrastructure are in place, the campus may consider technical options such as anaerobic digestion or plastic pyrolysis. Anaerobic digestion appears more feasible in the near term, while pyrolysis could become viable in the future as technology advances. A new MCA should be conducted when reconsidering these technologies, or new emerging technologies, to reflect future developments in cost and efficiency.

In summary, establishing a structured waste management strategy at the UNAM Sisal campus requires a phased approach:

Short-term (0–2 years)

- **Baseline study:** Conduct a full waste characterization following NMX-AA-061, -015, -022, and -019 to determine waste quantities and composition.
- **Monitoring:** Record monthly waste stream quantities and the level of contamination (incorrectly sorted materials) in each fraction to evaluate progress.
- **Connect potential partners:** Reconnect with the Secretaría de Desarrollo Sustentable and identify potential private recycling companies or NGOs for future waste collection and processing.

- **Pilot seperation system:** Implement a small-scale version of the Zero Waste Grassroots Programme with multi-bin separation for PET, paper, and organics in key areas (canteen, offices).
- **Composting pilot:** Start a small on-campus composting area for food and garden waste as part of the Zero Waste Programme, to reduce the amount of organic material ending up in the mixed waste stream
- **Awareness campaigns:** Apply elements from the Community-Based Social Marketing (CBSM) approach such as convenience, visual prompts, and student-led collection, to encourage correct separation.

Mid-term (2–5 years)

- **Scale up:** Introduce separation for additional fractions identified through the waste composition data (e.g., glass, metals).
- **Institutional integration**:Develop a more formal Integral Solid Waste Management Program that includes clear responsibilities, maintenance plans, and monitoring.
- **Community involvement:** Expand the system to include local residents or schools to strengthen collaboration between the campus and the Sisal community.
- **Technology review:** Evaluate new developments in waste treatment technologies (e.g., anaerobic digestion or plastic pyrolysis) and reassess their feasibility within the now established waste management system. Update the MCA accordingly.

Long-term (5-10 years): Advance toward circularity

- **Technology integration:** Reassess the feasibility of Anaerobic Digestion (AD), plastic pyrolysis, and other emerging recycling technologies again, as data and infrastructure improve. Explore opportunities to initiate pilot projects to test their practical performance and long-term feasibility.
- **Regional model:** Share best practices and results with other UNAM campuses and local authorities to replicate the Sisal model across Yucatán.

8

Roadmap

All three domains (energy, water, and waste) must ultimately come together in a single, integrated strategy that guides the Sisal campus toward the 2035 future vision, and to answer the central research question this report set out:

How can the UNAM Sisal campus become a self-sufficient and sustainable campus through integrated energy, waste, and water solutions that are technically feasible and aligned with stakeholder interests?

The roadmap presented on the following pages summarizes this answer, showing how the proposed measures collectively move the campus toward that goal.

When aligning the recommendations across all domains, several adjustments were made to ensure that the combined plan remains both feasible and coherent. Wind energy, although technically feasible, was excluded from the roadmap due to its limited potential contribution (around 10%) and higher visual and ecological impact compared to solar power. Given the campus's limited resources and the need to develop water and waste systems simultaneously, small-scale wind installations were considered unrealistic at this stage. Instead, the focus lies on scaling up solar generation and storage capacity, which can later power other systems (e.g., SSD and MBBR).

In the water domain, wastewater treatment is prioritized before desalination, as current discharges do not yet meet Mexican regulations. Desalination is therefore postponed until 2035, ensuring that available budgets are first directed toward improving water quality and establishing reliable treatment.

In the waste domain, pilot projects for more advanced technological solutions, such as anaerobic digestion or pyrolysis, are excluded from the roadmap. Implementing these systems alongside the energy and water plans would not be realistic in terms of both management capacity and available funding. Once all three domains are operating effectively, such technologies could be reconsidered as a future step. However, they are not a current priority given that a well-functioning recycling system already achieves all future goals.

Together, these coordinated steps form a phased and achievable pathway toward the future vision of a self-sufficient and sustainable UNAM Sisal campus.

2027

Energy

Baseline data, start projects, and promote energy efficiency

- Measure major energy consumers (e.g., AC units, pumps, labs) to establish a baseline.
- Install monitoring tools to track consumption throughout the day and failures.
- Start solar panel project (e.g., rooftops of main buildings) through partnerships; technical feasibility already proven.[1]
- Plan energy storage systems.
- Promote awareness among staff and students about energy consumption.
- Prepare groundwork for integration: data collected here will later feed into powering water treatment/desalination systems.

Water

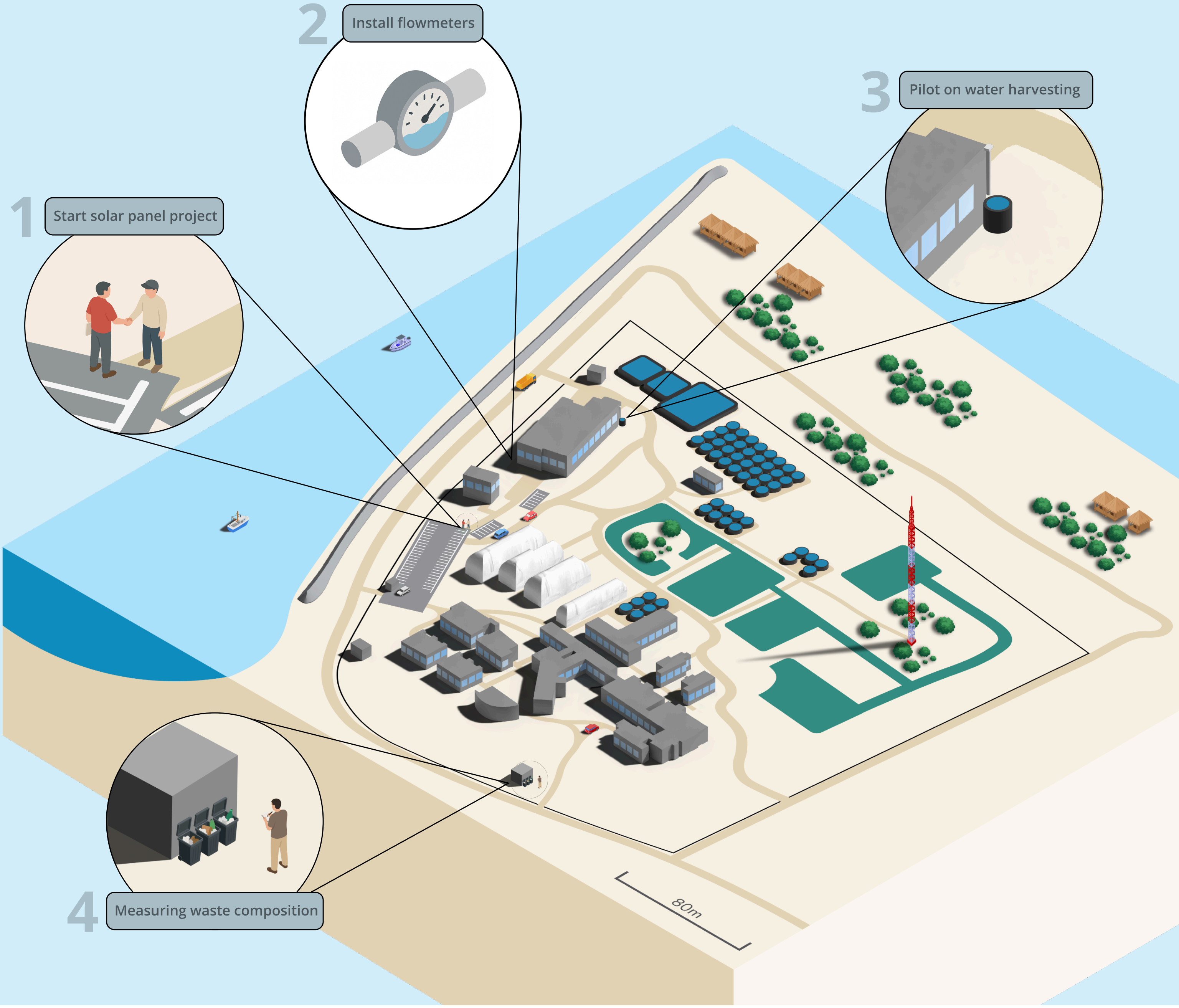
Understanding flows and preparing pilots

- Install flowmeters and monitoring of inflow/outflow to identify consumption and losses.[2]
- Secure funding and permits for desalinisation plant and MBBR.
- Assess water salinity and quality to determine whether desalination is viable in future.
- Coordinate with energy data collection to link treatment energy needs to future solar generation.
- Run pilot tests on AC-condensate and rainwater harvesting. [3]

Waste

Awareness, separation, and partnerships

- Measure waste composition to identify main sources and volumes.[4]
- Launch awareness campaign for waste separation across campus.
- Set up simple separation points (PET, paper, organic) and small composting pilot.
- Search for external recycling partners (e.g., Mérida-based cooperatives).
- Document process to integrate into future circular economy roadmap.



2030

Energy

50% renewable energy

- First solar panels installed and connected across main campus rooftops and lab buildings.[1]
- Behavioural energy reduction program in place, supported by awareness campaigns targeting lab equipment, AC, and lighting use.

Water

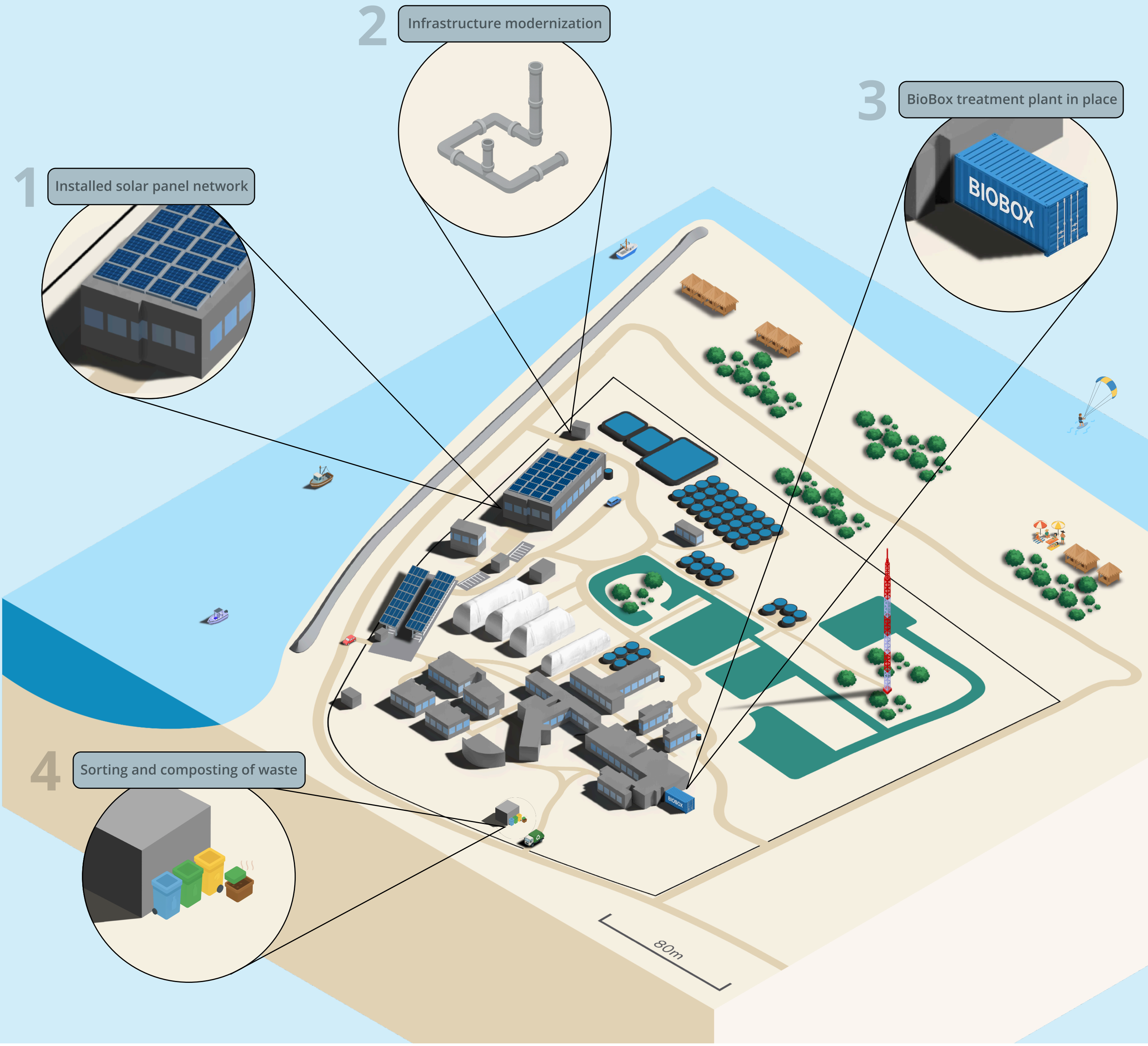
100% of wastewater treated

- Infrastructure modernisation of wells, tanks, and pipelines to improve reliability and reduce losses.[2]
- Full BioBox wastewater treatment plant constructed and operational, based on selected pilot technology.[3]

Waste

100% of waste seperated and treated

- Campus-wide waste separation system functional (e.g., PET, glass, paper, organic).[4]
- Composting scaled up from pilot to standard practice.[4]
- Partnerships with recycling cooperatives in place.
- Sisal community involvement in collection and education programs.
- Institutional integration of waste policies into UNAM operations and campus management.



2035

Energy

90% renewable energy

- The campus is discovering the possibilities to operate as a microgrid.
- More solar panels installed.
- Energy storage systems in place, balancing generation of energy and sustainable storage for power outages.[1]
- Energy system serves as a demonstrator for other UNAM sites and coastal research campuses.

Water

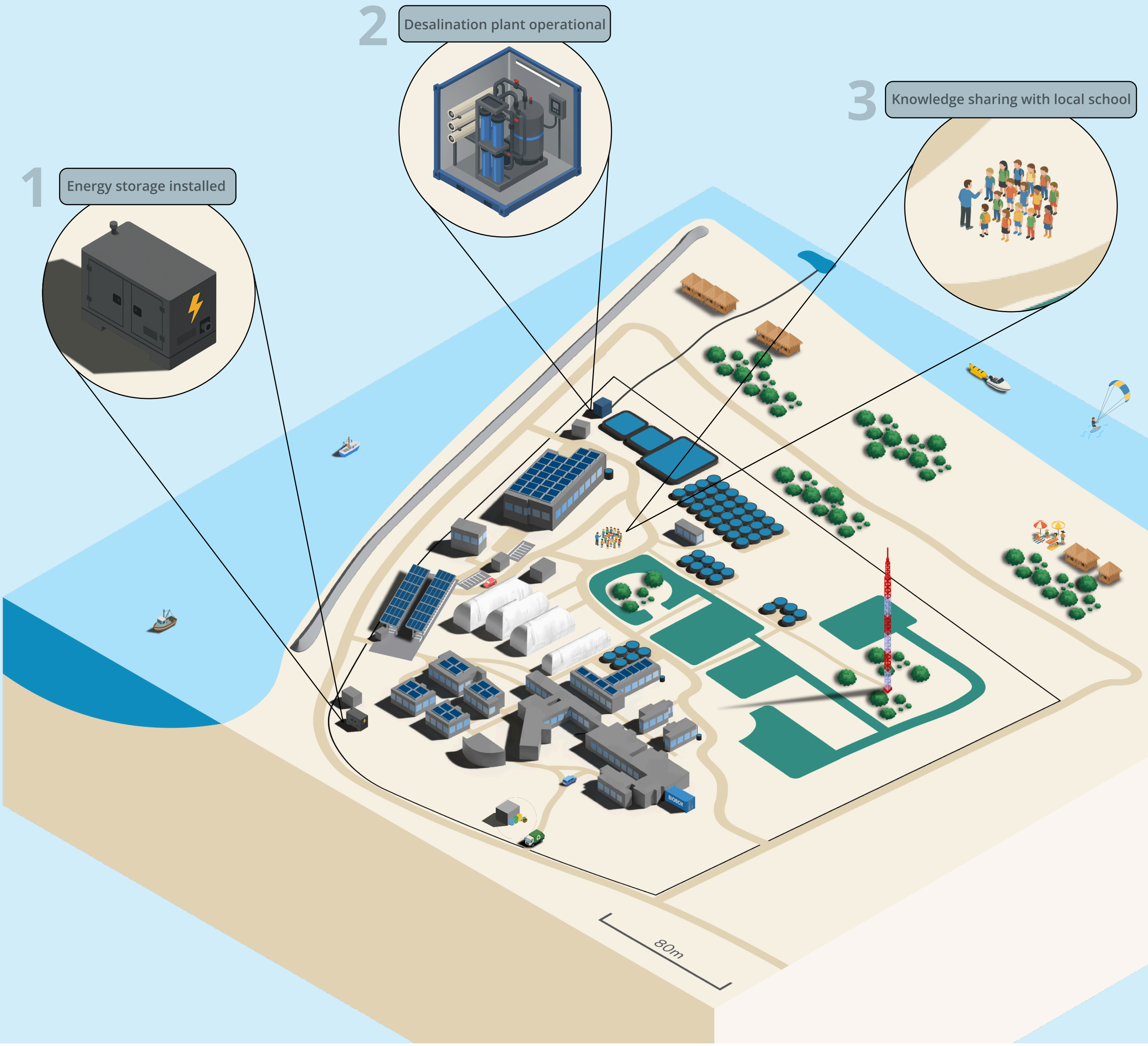
100% locally produced fresh water

- Desalination plant operational, producing potable water from seawater using renewable energy.[2]
- Visible, demonstrative systems used for education and outreach.
- Long-term maintenance and monitoring routines institutionalised, integrated into UNAM operational planning.

Waste

Circular economy and possible technology integration

- Full waste segregation maintained, with organic, plastic, and recyclable fractions. efficiently managed through local partners
- Technology integration explored, biogas recovery from organic waste.
- Knowledge sharing program established with Sisal community.[3]



2 Desalination plant operational

3 Knowledge sharing with local school

1 Energy storage installed

9
Discussion

This study aimed to develop an integrated sustainability roadmap for the UNAM Sisal campus by analysing and comparing potential solutions for water, waste, and energy systems. The research provides a foundation for future planning. However, the findings are subject to several limitations that must be considered when interpreting the results. This chapter discusses these limitations by first addressing general issues, followed by a domain-specific discussion for water, waste, and energy. Based on these discussions, it also gives reccommendations for future research.

9.1. Discussion

9.1.1. General

Short project timeframe
The limited timeframe of the project constrained the depth of analysis and the ability to verify implementation feasibility for all proposed solutions. Some potential interventions were therefore only evaluated at a conceptual level. This was mitigated by focusing on comparative analysis through the MCA and ensuring that the assumptions used were transparent and well-documented. The outcomes should thus be interpreted as directional strategies rather than finalized design proposals.

Furthermore, the restricted project duration also limited the scope of analysis for other important sustainability aspects such as mobility, community engagement and the role of external stakeholders. Although these themes were recognised and discussed in the assessment of the current situation, there was insufficient time to analyse them in detail or develop targeted recommendations. These topics are therefore suggested as priorities for future research.

Financial and Organisational Limitations
Although the proposed measures offer clear environmental benefits, their success will largely depend on the available funding and on how well the projects are organised. Most recommended systems require significant upfront investment and monitoring. Interviews with the campus staff and the Secretaría de Desarrollo Sustentable showed that there is currently no clear or secured budget for these sustainability projects, nor a long-term financial plan. In addition, the organisational structure for managing and maintaining such systems is not yet defined. Because this study did not analyse these aspects in depth, they may form practical barriers later on and could delay implementation if not properly addressed.

Context and Ambition of the Future Vision
The 2035 future vision was partly based on sustainability initiatives and goals developed at other university campuses, both in Mexico and abroad. However, these examples often come from institutions with more financial resources, making direct comparison difficult. While the goals were adapted to the local context, some targets, for example the aim of achieving 90% renewable energy, appear too ambitious after the analysis, given current conditions. Moreover, the general awareness and institutional support for sustainability in Mexico are still developing compared to countries like the Netherlands. This affects how quickly and strongly such plans can be implemented. The proposed goals should therefore be seen as a long-term direction rather than fixed targets.

Language Barriers
Most interviews and communications with local stakeholders were conducted in Spanish, which caused a language barrier. Despite translation assistance, some nuances and details may have been lost in translation. As a result, interpretations of stakeholder opinions or institutional procedures may not be entirely precise and should be treated with some caution. Efforts were made to verify all interview-based findings through follow-up discussions and cross-checking with other sources to ensure accuracy.

Sample size
The number of interviews and survey responses was limited by time and by the relatively small number of staff and students at the Sisal campus. Within these constraints, the collected input still provides a reasonable reflection of the main perspectives among the campus community. To complement the interviews, a short online survey was distributed among students to include their views as well. However, the limited number of responses could have effected the weighting process by making the MCA less robust, as it is based on a smaller dataset.

Research Bias and Cultural Influence
This research was conducted by a multidisciplinary team based in the Netherlands. The team's academic and cultural background may have influenced how sustainability and feasibility were perceived. In European contexts, sustainability is often more institutionalised and supported by policy and funding, which may have led to slightly optimistic expectations about what is achievable in Sisal. In addition, the academic disciplines represented within the team, such as industrial design, engineering, and policy, each come with their own perspectives and ways of thinking, which may have shaped how problems and solutions were approached. However, the multidisciplinary nature of the team helped to balance these viewpoints, reducing the impact of individual disciplinary bias and creating a more comprehensive and well-rounded analysis.

Group thinking
As the work was conducted collaboratively, there is a risk of bias in how findings were interpreted or prioritised, particularly during group discussions. To reduce this, results from different domains were cross-checked among team members, and key decisions were reviewed in supervision meetings and were verified with expert consultation and literature. Maintaining open discussion and using structured evaluation tools such as the MCA helped ensure that conclusions were based on evidence rather than consensus pressure.

9.1.2. Energy

Data gaps in wind and solar
Data for wind and solar resources were limited to short measurement periods. This introduces uncertainty in long-term variability and extreme value analysis, which can affect the accuracy of energy potential estimations. To mitigate this, the analysis combined local measurements with the ERA5 reanalysis dataset, corrected through Seasonal Quantile Mapping to align with observed conditions. While this approach increases reliability, the results should still be interpreted as indicative rather than exact.

Assumptions Sun
Several assumptions were made in estimating the solar energy potential, as outlined in chapter 5.1. While these assumptions are well supported by literature and field input, they inevitably introduce uncertainty into the results. Future studies should therefore prioritise on-site measurements and structural assessments to validate these assumptions and refine the accuracy of the potential estimates.

Wind scenario and system boundaries
The wind energy potential was calculated based on a pilot setup of five small-scale turbines, which occupy an estimated total footprint of around 100 m^2. This number was considered a realistic starting point, as potential side effects such as noise disturbance, bird interactions, and wake effects between turbines have not yet been assessed. As a result, the estimated contribution of 4.1–10.9% should be interpreted as scenario-dependent rather than a maximum potential.

Storage and reliability considerations
The scores for the reliability criterium in the MCA implicitly assume the presence of either battery storage or a stable connection to the electrical grid. Without such systems, energy curtailment is likely to occur during periods of high solar production or low demand, which would reduce the effective contribution of renewable sources, also during outages. Future work should therefore include an evaluation of storage requirements and control systems to ensure operational stability.

Sensitivity of results
The economic outcomes for both solar and wind are sensitive to input parameters such as capital costs, inflation rate and system degradation. A short sensitivity analysis, for example by varying CAPEX, the inflation rate, and degradation, would help to better understand the robustness of the financial analyses

Policy and permitting constraints
Uncertainties remain regarding regulatory and permitting aspects. The conditions for net metering and energy compensation with the electricity provider (CFE) are not yet defined, which could influence the business case for renewable energy generation. For wind energy, additional constraints may arise from visual, noise, and ecological (bird) assessments. Whereas for solar energy, structural approval must be verified. These aspects represent practical implementation risks that should be addressed early in the planning process.

9.1.3. Water

Data availability and representativeness
The analysis of water use and treatment was limited by the availability and quality of data. Records on water extraction, consumption, and discharge were often incomplete or inconsistent, making it difficult to calculate total water use with high accuracy. Where possible, missing information was supplemented by comparing data from different months and by using reference figures from previous UNAM studies on the Sisal campus Sagastume (2022). These estimates provide a general indication of current conditions but should be regarded as approximations rather than precise values.

Similarly, the rainwater harvesting potential was estimated using regional rainfall data using open source rainfall data. While these data give a reasonable indication of the climate, local coastal effects such as wind patterns and microclimate variations may cause slight deviations in actual rainfall. To improve reliability in future studies, systematic on-site monitoring of rainfall, water consumption, and wastewater discharge is recommended to build a complete and representative dataset for the campus.

Assumptions in cost and yield estimates
Several financial and technical values, such as investment costs, operational expenses, and expected water yields, were taken from literature and supplier information. These assumptions are suitable for comparing the performance of different systems but make the absolute results less certain. The findings should therefore be interpreted as indicative. Before implementation, pilot projects and updated supplier quotations should be used to verify system costs and performance under local conditions.

9.1.4. Waste

Data limitations
The waste domain was analysed primarily through literature and case studies from comparable university campuses, as quantitative data from UNAM Sisal were not available. This lack of site-specific information, such as waste quantities and composition, is the main limitation of the study. It prevented detailed assessment of waste streams or potential impacts of the proposed solutions, such as recycling rates or cost–benefit outcomes. As a result, the Multi-Criteria Analysis (MCA) was based largely on assumptions and qualitative insights from literature, making the analysis more conceptual than those for water and energy.

Dependence on external partners
Another key limitation is the system's dependence on external partners. The proposed Zero Waste Grassroots Programme relies on NGOs or recycling companies to collect and process separated waste, which may be difficult to secure given Sisal's remote location. Without these partnerships, the program cannot function effectively, as the campus currently lacks the capacity, infrastructure, and permits to handle or process waste independently. These challenges were acknowledged in the report, but they remain critical to address in future planning and research to ensure that the waste management strategy is both practical and sustainable.

9.2. Future research

Several directions for future research arise from the limitations and findings discussed in this study. As mentioned in the previous sections, recommendations have already been made, including conducting sensitivity analyses for key economic parameters, validating assumptions through on-site measurements, and examining the regulatory and organisational factors that may influence implementation. Building on these points, the following directions for future research are suggested to further develop and strengthen the sustainability strategy for the UNAM Sisal campus.

A first priority for future research should be the systematic collection and analysis of local data. Reliable information on energy use, water consumption, wastewater generation, and waste composition is still lacking but is essential for informed decision-making. Future studies could therefore focus on developing a consistent monitoring framework for these parameters. For example, through the use of smart meters, flow sensors, or periodic sampling. Such research could also explore how these datasets can be integrated into campus management systems to improve long-term monitoring and evaluation.

Once a solid data foundation is in place, future research could advance the detailed design and testing of the most promising technical solutions identified in this study. This might include the pilot implementation of modular wastewater treatment systems such as the MBBR, or feasibility studies on a solar-based microgrid with energy storage that can handle the frequent poweroutages. These studies could also assess practical aspects such as operation, maintenance, and staff training to ensure long-term reliability. In parallel, attention should be given to the institutional and organisational problems mentioned that influence project implementation to ensure that proposed systems can be realistically adopted and sustained over time.

Additionally, future research could further explore mobility and community engagement, two themes that were recognised in this study but not analysed in depth. A focused investigation into mobility could examine how students and staff travel to and within the campus, identify key challenges such as limited public transport or infrastructure, and propose realistic strategies to reduce emissions from daily commuting. Similarly, future studies could explore how the Sisal campus can strengthen its connection with the local community through education, shared sustainability projects, or resource exchange. Understanding these social dimensions would help integrate sustainability more broadly across both the campus and the town, ensuring that future initiatives create mutual benefits.

Finally, future studies could extend the analytical scope by testing the robustness of the financial and environmental assessments used in this research. Sensitivity and uncertainty analyses that examen how changes in costs, resource availability, or climatic conditions affect system performance would provide a more realistic picture of long-term feasibility.

Overall, future research should aim to move from conceptual planning toward a more data-driven and operational approach. Combining continuous monitoring, pilot implementation, and community engagement will allow the Sisal campus to evolve into a practical and replicable model for sustainable development in coastal regions of Mexico.

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A

Data Collection Solar and Wind

This appendix presents the data collection performed during this study. In Table A.1 an overview is given with all the available data considered in this report. The data can be divided in two categories: local measurements (UNAM 1 and UNAM 2) and reanalysis computed measurements (ERA5 and CFSV2). The local measurements are more accurate but have a limited measurement period. To build a realistic database with a sufficient timespan and acceptable accuracy, this report combines reanalysis data with local measurements. The adjustments to the solar and wind data are explained in Appendix B and C, respectively.

Table A.1: Grouped overview of data sources by category with heights (AMSL), variables, measurement period, and organization.

Entry	Height(s) AMSL [m]	Variables	Measurement period	Organization
Wind				
hourly ERA5	10, 100	u & v components	1940-present	Copernicus (CDS)
6-hourly CFSV2	10	u & v components	2011-present	NCEP
hourly UNAM 1	23.7	Avg & Max Wspeed and Wdir	2017/07/01-present	UNAM (Sisal)
hourly UNAM 2	3, 6, 12.5, 25, 51	u & v components	2010/08-2014/11	UNAM (Sisal)
Solar				
hourly ERA5	2	cdir, ssr, fdir	1940-present	Copernicus (CDS)
6-hourly CFSV2	2	ghi_Whm2_6h; ghi_wm2	2011-present	NCEP
hourly UNAM 1	23.7	Rad_Avg	2017/07/01-present	UNAM (Sisal)

Notes: **cdir** = clear-sky direct solar radiation at the surface; **ssr** = surface net shortwave radiation (down minus up); **fdir** = all-sky direct solar radiation at the surface; **ghi_Whm2_6h** = global horizontal irradiation integrated over 6 h [$\mathrm{Wh\,m^{-2}}$]; **ghi_wm2** = global horizontal radiation (time-step mean) [$\mathrm{W\,m^{-2}}$]; **Wdir** = wind direction (degrees from north, direction wind comes from).

ERA5 was selected as the reanalysis dataset in place of CFSv2. ERA5 provides a longer record and a higher resolution, offering hourly measurements instead of 6-hourly. The UNAM1 dataset is very accurate for wind measurements, but performs less well for solar variables. In particular, multiple radiation spikes are present, including during nighttime. The treatment of these spikes is described in Appendix B.

B

Solar Energy

B.1. Data adjustments

As noted in Appendix A, the UNAM1 record contains too many faulty values for quantile mapping. Nevertheless, a bias correction was applied because visual inspection showed that ERA5 underestimates solar radiation compared with UNAM1, see Figure B.1. ERA5 was scaled by a constant factor chosen to minimize the mean squared error against the filtered UNAM1 data. Factors from 0.9 to 1.5 were tested in 200 steps. The minimum error occurred at 1.09, see Figure B.2. The changes of the ERA5 data due to the scale factor are shown in Figure B.3.

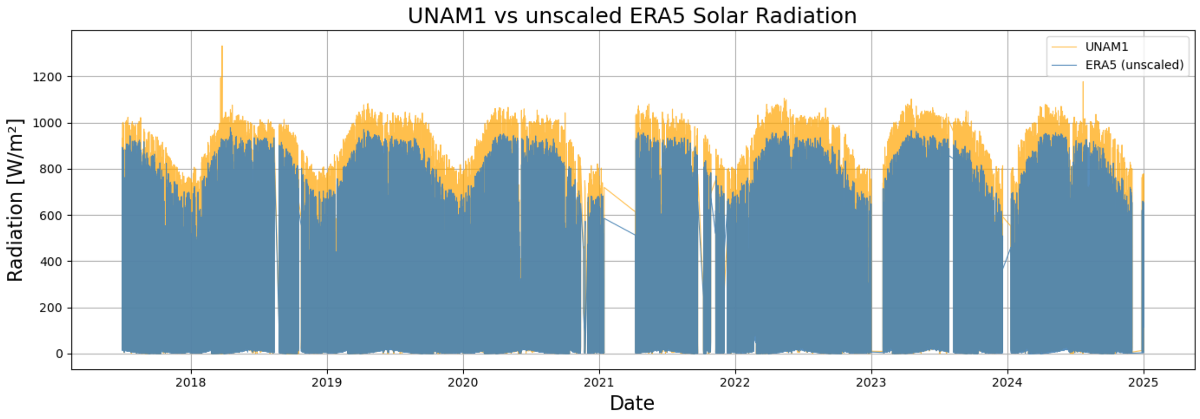
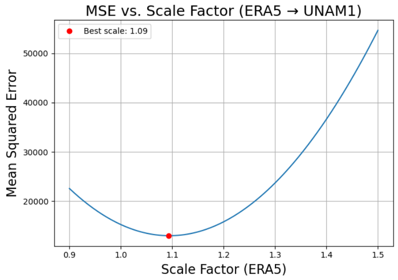


Figure B.1: Overlap UNAM1 and unscaled ERA5



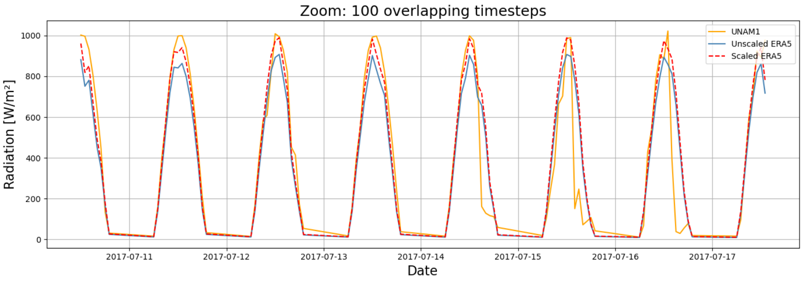


Figure B.2: MSE vs Scale factor

Figure B.3: UNAM1 vs unscaled/scaled ERA5

B.2. Potential Energy generation

In this report the minimum/maximum values for yearly potential energy generation by solar panels are used from the paper of Morcillo-Herrera et al. (2014). This casestudy tests 5 different solar panels in Mérida with an annual energy yield (AEY) ranging from:

$$AEY^{2014}_{\text{min}} = 182.04 \text{ kWh m}^{-2} \text{ yr}^{-1}; AEY^{2014}_{\text{max}} = 225.36 \text{ kWh m}^{-2} \text{ yr}^{-1} \tag{B.2.1}$$

Assuming that Sisal and Mérida experience comparable radiation given their 40 km separation (approximately), the Mérida values are taken as reasonable estimates for Sisal. This assumption is supported by the close match between the monthly mean radiation curves shown in Figure B.4 and Figure 6(a) of the Mérida case study (Morcillo-Herrera et al., 2014), both based on the 2010–2014 period.

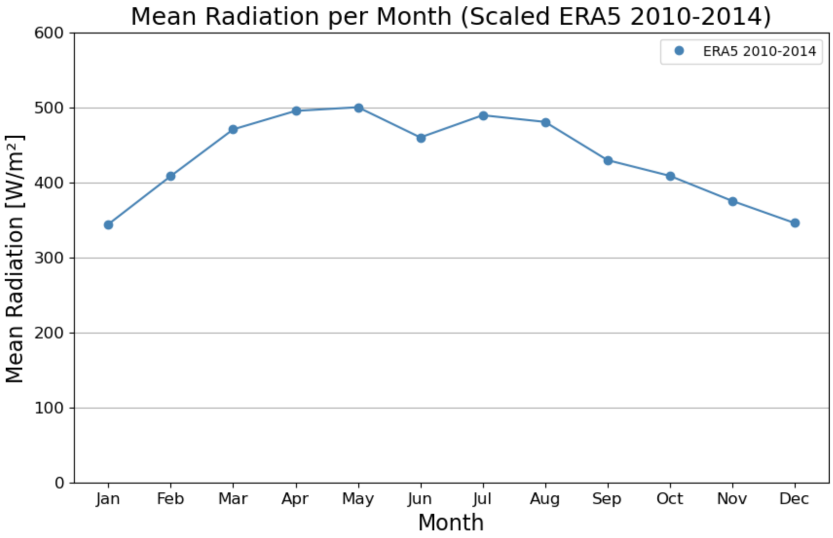


Figure B.4: Radiation daily average monthly

The monthly profile of potential energy yield (EY) is derived from B.2.1. These values still need to be adjusted to give a more realistic insight for 2024, since the values are simplistic (yearly) and outdated (2014). The adjustments are:

1. **Increased efficiency solar panels** Potential annual energy yields reported for 2014 in Morcillo-Herrera et al. (2014) are adjusted to reflect improved module efficiency in 2024 by a constant factor $r = 1.375$. This factor is based on the paper of Philipps and Warmuth (2025). Here the global efficiëncy of solar panels increases from 16% to 22% in the timespan from 2014 to 2024:

$$AEY^{2024}_{\text{min}} = r\,AEY^{2014}_{\text{min}} \;\; [\text{kWh m}^{-2}\text{ yr}^{-1}]; \qquad AEY^{2024}_{\text{max}} = r\,AEY^{2014}_{\text{max}} \;\; [\text{kWh m}^{-2}\text{ yr}^{-1}] \quad \text{(B.2.2)}$$

2. **Monthly radiation fluctuation** The radiation magnitude is different throughout the year, see Figure B.5. A timeframe of 2014 - 2024 is used from the scaled ERA5 dataset to identify which months correspond to higher/lower solar radiation. This 11-year window reduces year-to-year variability while remaining recent and representative of current conditions. To find the scale factor for each month, radiation for each month is divided by the yearly mean radiation:

$$p_m = \frac{\text{SSR}_m}{\frac{1}{12}\sum_{m=1}^{12}\text{SSR}_m} \quad [-] \qquad \text{(B.2.3)}$$

(Here, SSR_m denotes the mean solar radiation for month m.)

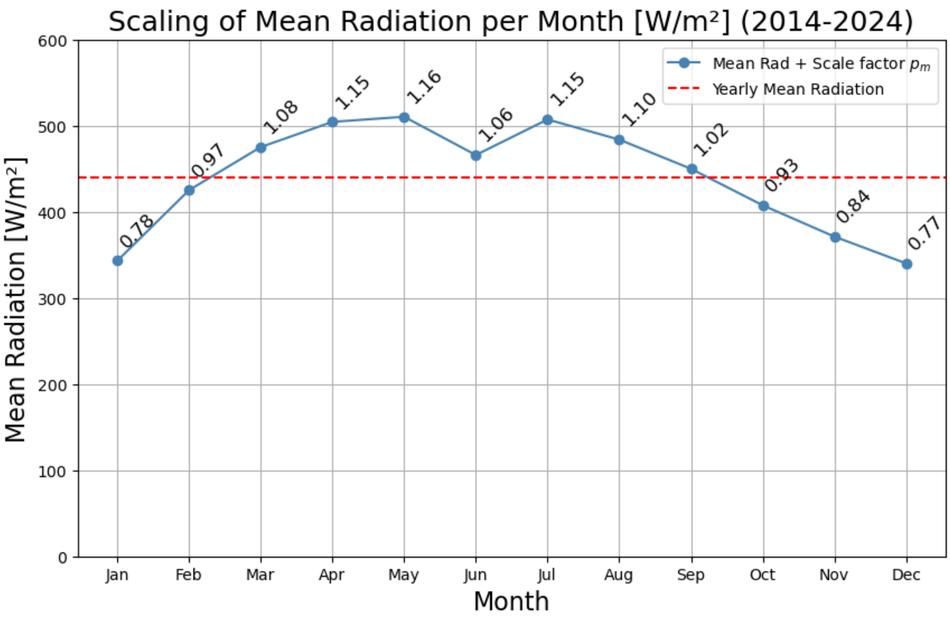


Figure B.5: Monthly Mean Radiation and Scalefactors

The potential energy yield in 2024 for each month can be stated by:

$$EY^{2024}_{m,min} = p_m \cdot r \cdot \frac{AEY^{2014}_{\text{min}}}{12} \text{ [kWh m}^{-2}\text{ mo}^{-1}]; \quad EY^{2024}_{m,max} = p_m \cdot r \cdot \frac{AEY^{2014}_{max}}{12} \text{ [kWh m}^{-2}\text{ mo}^{-1}] \quad \text{(B.2.4)}$$

The adjusted expected EY per month is visualized in Figure B.6. An overview of the expected EY for each month is shown in Table B.1. The values under the part 'Specific' can be used to asses different potential area's.

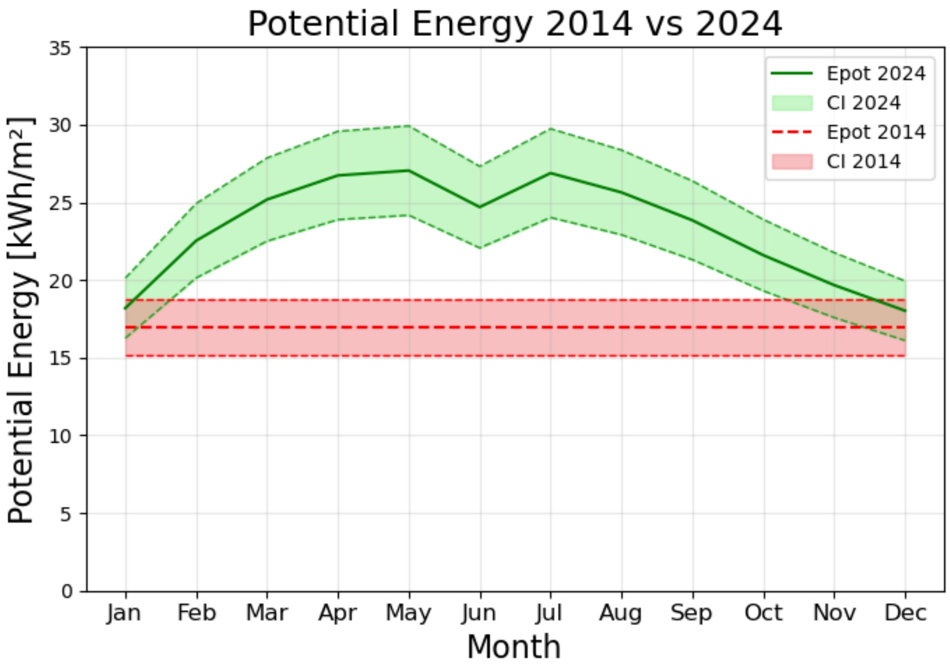


Figure B.6: Energy yield 2014-2024

Table B.1: Monthly potential energy yield (2024): specific per m^2 vs. total (area included)

Month	Specific [kWh m^{-2}]			Total [kWh]		
	$EY^{2024}_{m,\text{min}}$	$EY^{2024}_{m,\text{max}}$	$EY^{2024}_{m,\text{mean}}$	$EY^{2024}_{m,\text{min}}$	$EY^{2024}_{m,\text{max}}$	$EY^{2024}_{m,\text{mean}}$
Jan	16.25	20.12	18.19	31 999	39 614	35 807
Feb	20.14	24.93	22.53	39 643	49 077	44 360
Mar	22.51	27.86	25.19	44 309	54 853	49 581
Apr	23.89	29.58	26.74	47 083	58 232	52 635
May	24.18	29.93	27.05	47 592	58 917	53 254
Jun	22.07	27.33	24.70	43 452	53 793	48 623
Jul	24.03	29.75	26.89	47 300	58 556	52 928
Aug	22.92	28.37	25.65	45 118	55 855	50 487
Sep	21.31	26.39	23.85	41 959	51 944	46 951
Oct	19.31	23.90	21.60	38 088	47 053	42 530
Nov	17.58	21.77	19.68	34 616	42 853	38 734
Dec	16.11	19.94	18.03	31 715	39 262	35 489

Note: Totals are computed in this report using a potential area *Potential Area* $= 3821 \times 0.6 = 2\,292$ m^2.

C
Wind Energy

C.1. Data adjustments

To correct for the difference in measurement heights between the ERA5 dataset and the local UNAM1 data, a wind profile was created using the UNAM 2 dataset. It contains the average daily wind speeds at different heights. The average profile of all measurements is shown as the red line in Figure C.1.

The ERA5 data measured at 10 m AMSL is extrapolated to 23.7 m to match the UNAM 1 dataset. This vertical extrapolation of the wind speed is performed with both the log law (Equation C.1.1) and the power law (Equation C.1.2) (El Khachine et al., 2025). As shown in Figure C.2, the power law provides the best fit to the measured means.

$$U(z) = U_r \frac{\log\left(\frac{z}{z_0}\right)}{\log\left(\frac{z_r}{z_0}\right)} \quad [m \ \ s^{-1}] \tag{C.1.1}$$

$$U(z) = U_r \left(\frac{z}{z_r}\right)^{\alpha} \quad [m \ \ s^{-1}] \tag{C.1.2}$$

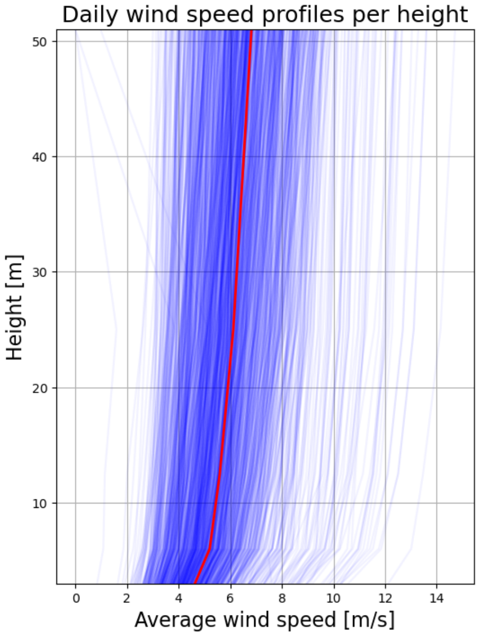


Figure C.1: Daily average wind speed profiles per height AMSL

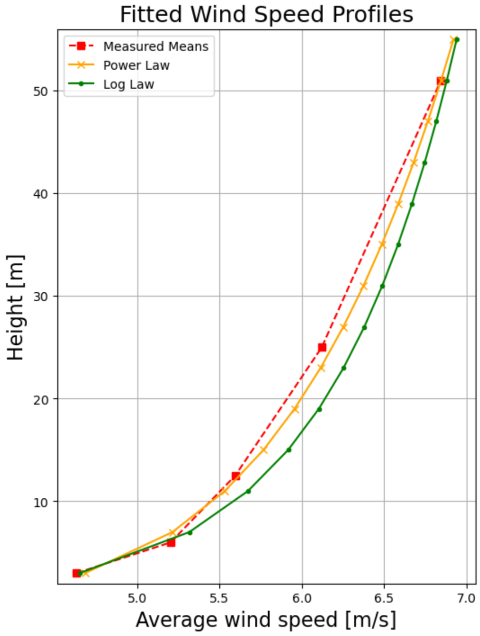


Figure C.2: Extrapolated avarage wind speed profiles per height AMSL

From the power law fit, the exponent α is obtained. The factor $\left(\frac{z}{z_r}\right)^{\alpha}$, with $z = 23.7$ m and $z_r = 10$ m, scales the ERA5 data to the measurement height of the UNAM 1 dataset.

The scaled ERA5 dataset still differs from the local measurements because of the coarse grid of the ERA5 model. Local values are estimated through interpolation, which reduces accuracy. A bias correction is applied to improve the model by using seasonal quantile mapping. This method aligns the ERA5 distribution with the observed distribution from UNAM 1. Before applying the correction, data points missing in the local dataset are also removed from the scaled ERA5 data. This prevents gaps in the observations from affecting the correction. The dataset is evaluated in four configurations:

1. The unprocessed (raw) data
2. Data corrected using full-sample quantile mapping (QM)
3. Data processed with seasonal quantile mapping using two seasons (2SQM; wet and dry seasons)
4. Data processed with seasonal quantile mapping using four seasons (4SQM; spring, summer, autumn, and winter)

For each configuration, an extreme-value analysis is performed; see Section C.2. The 2SQM configuration yields the most favorable performance.

The 2SQM corrected dataset is shown in Figure C.3. Figure C.4 provides a detailed view of the overlapping period of both datasets in which quantile mapping is performed. Figure C.5 shows how trends and peaks are captured.

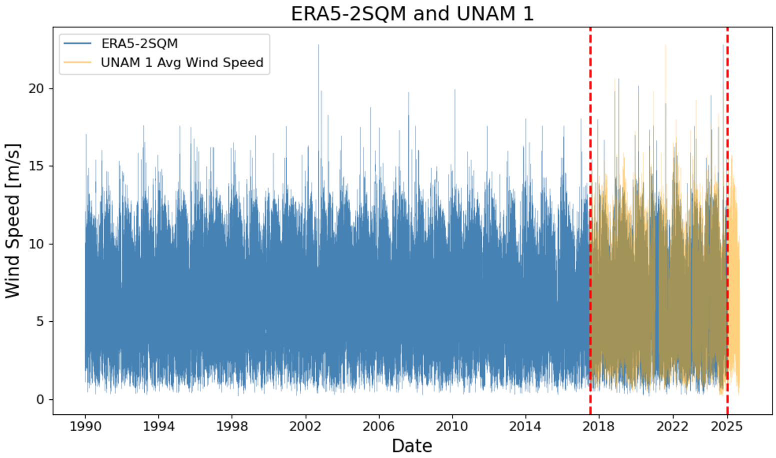


Figure C.3: Time series from ERA5-2SQM and UNAM1 dataset

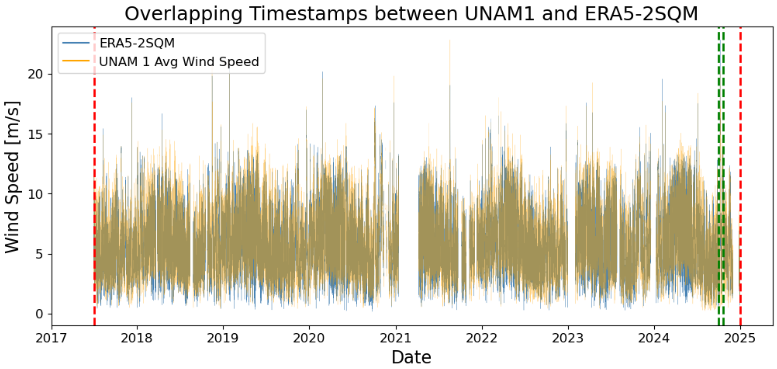


Figure C.4: Overlapping time series from ERA5-2SQM and UNAM1 dataset

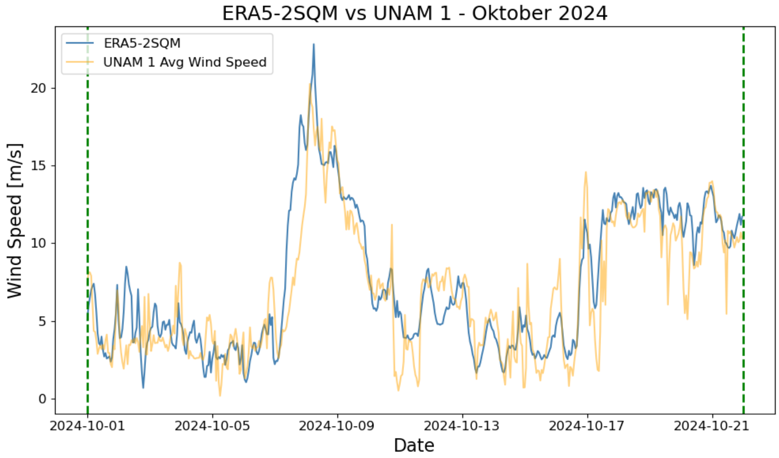


Figure C.5: Monthly view of time series from the ERA5-2SQM and UNAM1 dataset

The PDF and ECDF in Figures C.6 and C.7 show how the ERA5 dataset changes after the 2SQM.

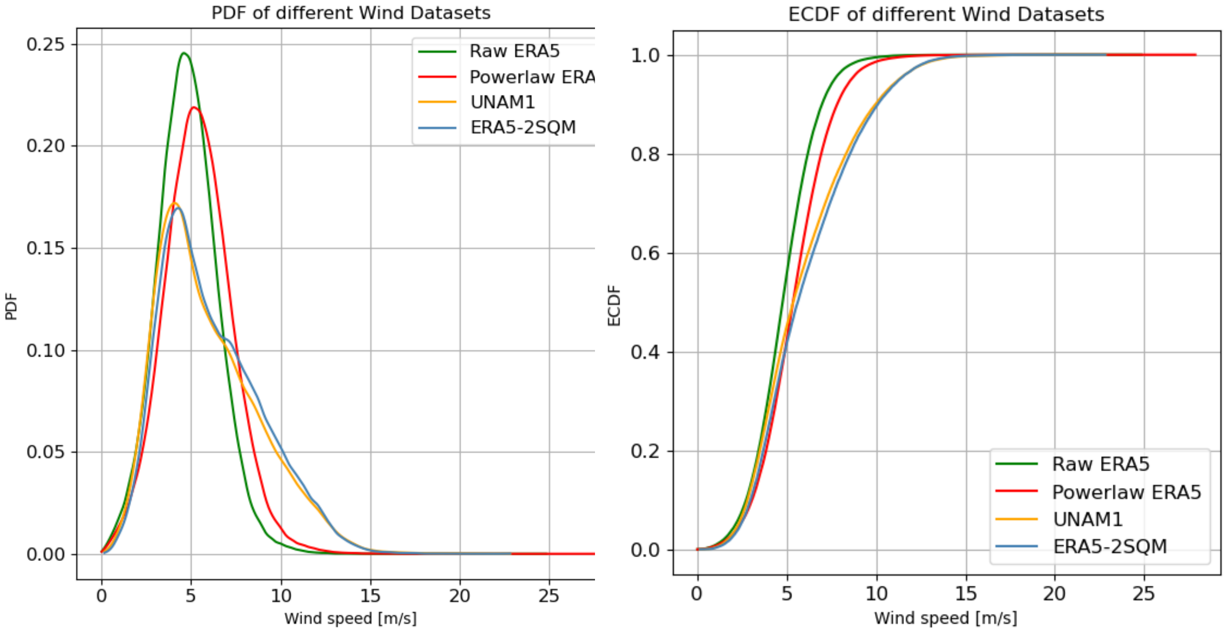


Figure C.6: PDF

Figure C.7: ECDF

C.2. Extreme Value Analysis

The threshold ranges reported in Table C.1 were determined as follows. For parameter stability plots, the selected range corresponds to the region where the estimated parameters remain relatively stable and do not exhibit strong fluctuations. In the mean residual life (MRL) plots, the valid range is identified as the interval where the graph shows a linear trend. For the return value stability plots, the range is chosen based on the section where the return level estimates remain approximately constant, indicating horizontal behavior. Smaller AIC values and less negative loglikelihood values correspond to better models (Bocharov, 2022). A Q-Q (quantile-to-quantile) plot compares the quantiles of two distributions, while a P-P (probability-probability) plot compares the cumulative probabilities of two distributions. Q-Q plots are better for assessing the overall fit of a distribution and are more sensitive to deviations in the tails, whereas P-P plots are better at detecting deviations in the center of the distribution. Considering the AIC, Loglikelihood, Q-Q plot and P-P plot the ERA5-2SQM dataset is named the best-fitting model (Wilk & Gnanadesikan, 1968).

Table C.1: Threshold analysis summary by dataset

Metric	Raw ERA5	ERA5-QM	ERA5-2SQM	ERA5-4SQM
Parameter Stability	5–12	12–16	5–16	5–15
Mean Residual Life	7–10	10–12	10–13	10–13
Return Value Stability	7–13	12–17	13–17	12–14
Threshold	7	12	13	13
AIC	2879	1998	1111	1286
Loglikelihood	−1437	−996	−553	−641
QQ-plot	0.988	0.994	0.997	0.995
PP-plot	0.999	0.999	0.998	0.997

For illustration purposes, the plots of the corresponding threshold selection metrics for ERA5-2SQM are shown in Figure C.8, Figure C.9 and Figure C.10. After threshold selection, the peak over threshold analysis is shown in Figure C.11. This is a Generalized Pareto Distribution (GPD) (Table C.1). The number of extremes identified is 398 out of 306816 total data points. The Goodness of Fit is summarized in Figure C.12 and Table C.2. The 100-year return level for wind speed at 23.7m is 22.84 m/s with a 95% confidence interval of (26.37 - 30.79) m/s, see Figure C.13. The function used to obtain these values has a slight fluctuation. Therefore, the maximum wind speed accounted for in this report is 31 m/s.

The alternative plots and tables (of the other datasets) can be found in the complementary programming folder, which is placed in the repository on zenodo.com. For acces, contact j.j.devos@student.tudelft.nl.

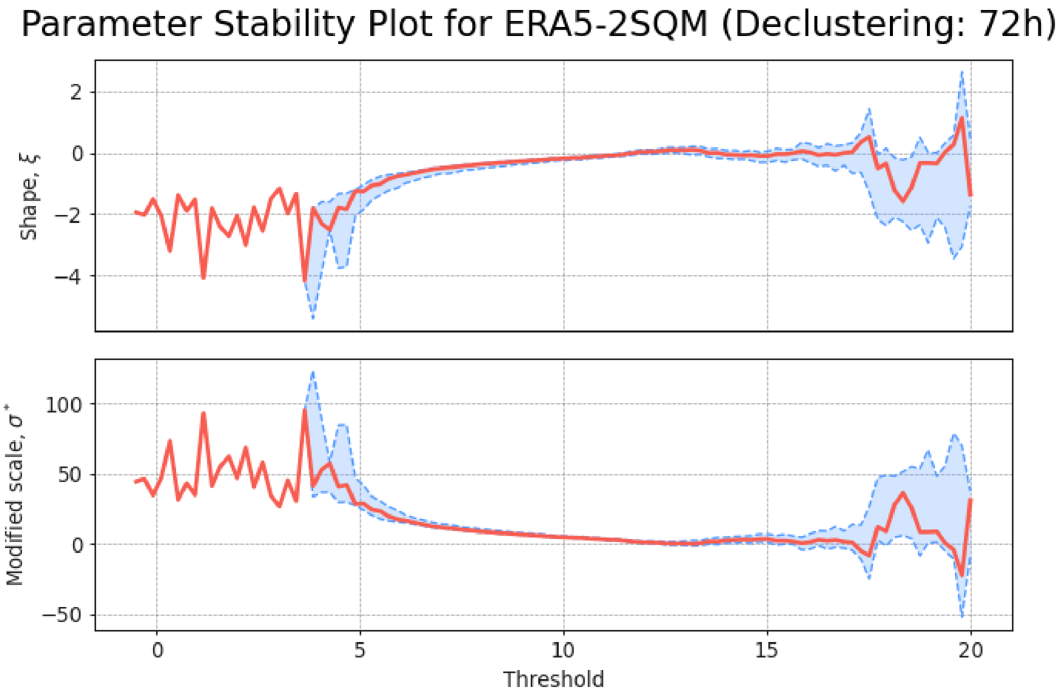


Figure C.8: Parameter Stability ERA5-2SQM

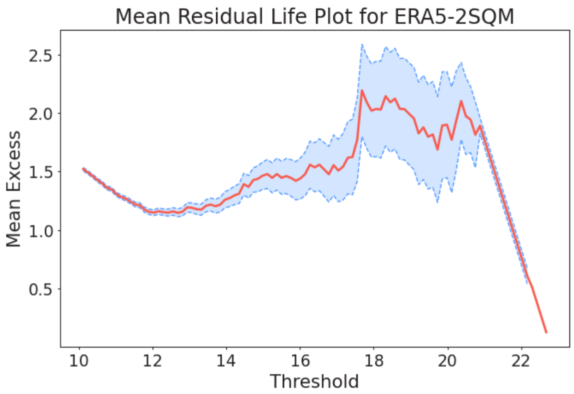


Figure C.9: Mean Residual Life ERA5–2SQM

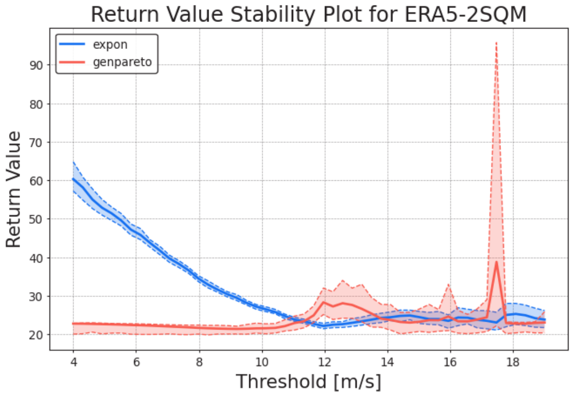


Figure C.10: Return Value Stability plot

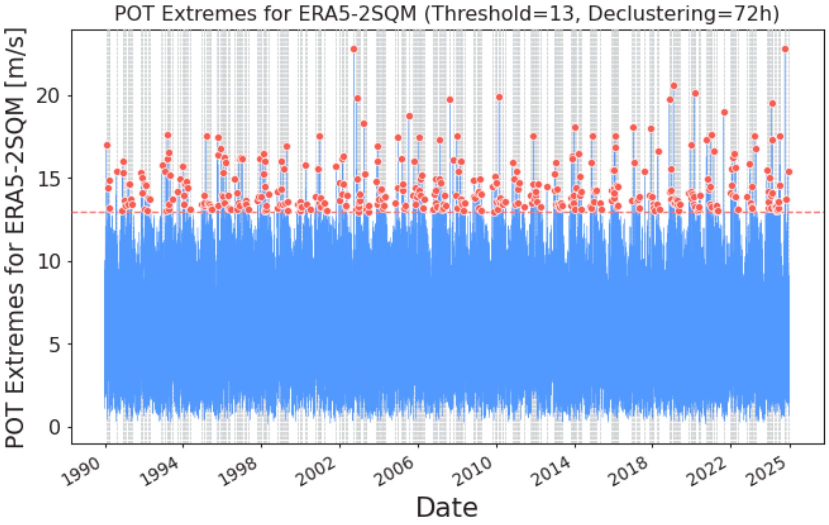


Figure C.11: Peak over Treshhold

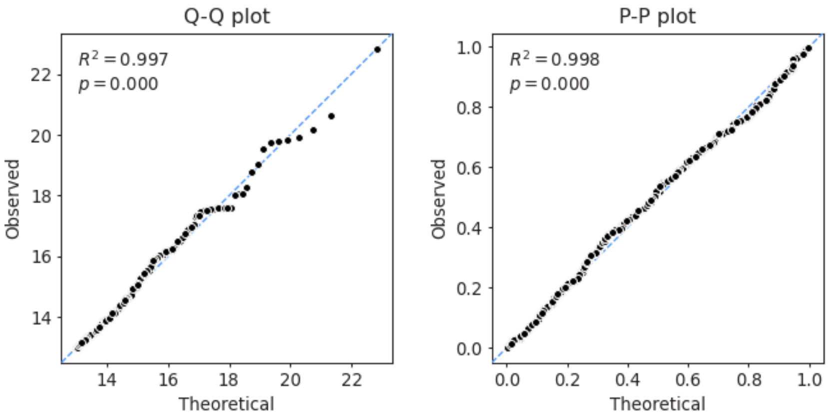


Figure C.12: Goodness of Fit

Table C.2: MLE ERA5-2SQM model

MLE model	
Free parameters	$c = 0.093$, scale $= 1.348$
Fixed parameters	$floc = 13.000$
AIC	1111.417
Log-likelihood	-553.693
Number of extremes identified	398

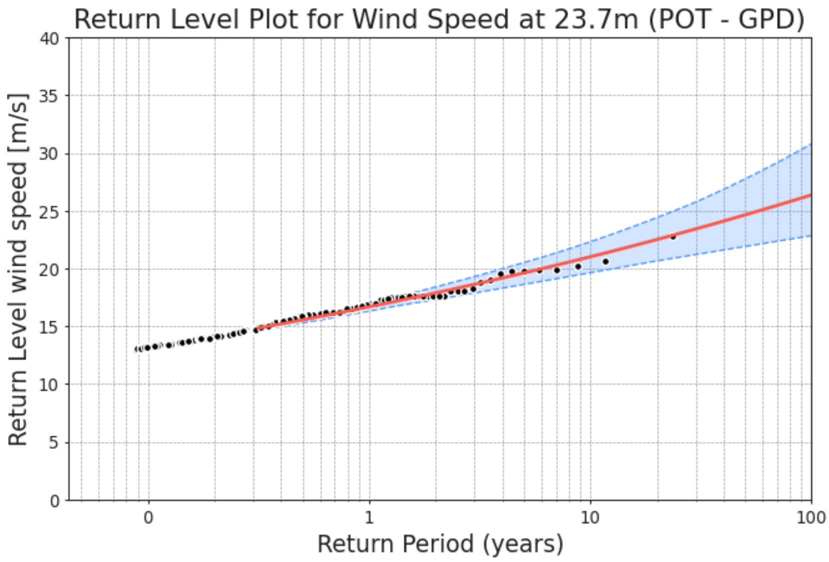


Figure C.13: Return level Wind Speed

C.3. Potential Energy Generation

When calculating the potential energy generation due to wind energy, the following steps are taken. These steps can be taken for all possible windturbines and this can be done in the zenodo repository.

Symbols

Table C.3: Key input parameters used for the small-scale wind-turbine energy-yield method

Parameter	Unit	Small-scale wind turbine
ρ air density	[kg m^{-3}]	1.225
A rotor swept area	[m^2]	36
C_p power coefficient	[–]	0.45
P_{rated} rated electric power	[kW]	5
v_{ci} cut-in wind speed	[m s^{-1}]	2.5
v_{r} rated wind speed	[m s^{-1}]	11.0
v_{co} cut-out wind speed	[m s^{-1}]	16.0
N number of wind-speed bins	[–]	N (e.g., 1000)
Δv bin width	[m s^{-1}]	$(v_{\text{max}} - v_{\text{min}})/N$
v_{min} lower limit for binning	[m s^{-1}]	typically $v_{\text{ci}} = 2.5$
v_{max} upper limit for binning	[m s^{-1}]	typically $v_{\text{co}} = 16.0$

Step 1: Power Curve

The turbine power as a function of wind speed v is given by:

$$P(v) \quad [kW] = \begin{cases} 0, & v < v_{\text{ci}}, \\ \dfrac{1}{1000}\,\dfrac{1}{2}\,\rho\,A\,C_p\,v^3, & v_{\text{ci}} \le v < v_{\text{r}}, \\ P_{\text{rated}}, & v_{\text{r}} \le v < v_{\text{co}}, \\ 0, & v \ge v_{\text{co}}. \end{cases} \tag{C.3.1}$$

We discretize the wind-speed axis with N bins:

$$\Delta v \;=\; \frac{v_{\text{max}} - v_{\text{min}}}{N}, \quad b_k \;=\; \big[v_{\text{min}} + k\,\Delta v,\; v_{\text{min}} + (k+1)\,\Delta v\big], \quad v_b \;=\; v_{\text{min}} + \left(k + \tfrac{1}{2}\right)\Delta v, \quad P_b \;=\; P(v_b). \tag{C.3.2}$$

with $k = 0, \ldots, N-1$.

An example of a power curve is shown in Figure C.14.

Step 2: Wind-Speed Binning

Assume we have Y years (e.g., $Y = 25$) ranging from 2000 until 2025, where 2000 corresponds to $y = 1$. Count the time spent in each bin. Let $h_{y,m}(b)$ be the total hours in year y and month m that fall into bin b. This gives you the frequency distribution of wind speeds per month. A visual example of such a distribution is shown in Figure C.15

Step 3: Monthly and Annual Energy Yield

For each year y and month m, the monthly Energy Yield (EY) is given by:

$$\text{EY}_{y,m} \;=\; \sum_b P_b\,h_{y,m}(b) \quad [kWh \;\; mo^{-1}] \tag{C.3.3}$$

The Annual Energy Yield (AEY) for year y is the sum of that year's monthly yields:

$$\text{AEY}_y \;=\; \sum_{m=1}^{12} \text{EY}_{y,m} \quad [kWh \;\; yr^{-1}] \tag{C.3.4}$$

Interpretation: (C.3.3) integrates power (C.14) over the time spent at each wind-speed bin (C.15); (C.3.4) aggregates months to an annual figure.

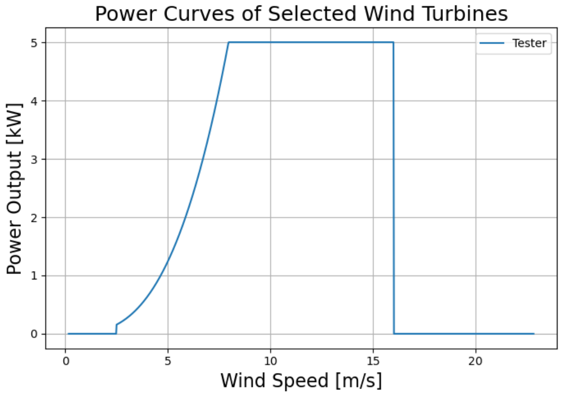


Figure C.14: Example Powercurve Wind Turbine

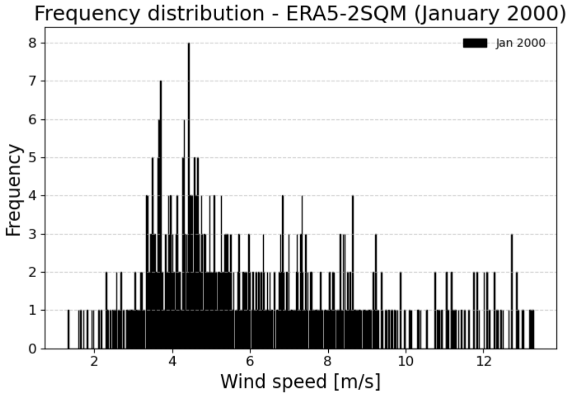


Figure C.15: Monthly frequency distribution $h_{1,1}$

Step 4: Make expectations on

Collect, for each calendar month m, the set of monthly yields across years:

$$\mathcal{S}_m = \{\text{EY}_{1,m}, \text{EY}_{2,m}, \ldots, \text{EY}_{y,m}\} \tag{C.3.5}$$

Define the expected monthly yield (sample mean) and min/max bounds:

$$\overline{\mathsf{EY}}_m = \frac{1}{Y}\sum_{y=1}^{Y}\mathsf{EY}_{y,m} \quad [kWh\ \ mo^{-1}] \tag{C.3.6}$$

$$\mathsf{EY}_m^{\mathsf{min}} = \mathsf{min}\,\mathcal{S}_m \quad [kWh\ \ mo^{-1}]; \qquad \mathsf{EY}_m^{\mathsf{max}} = \mathsf{max}\,\mathcal{S}_m \quad [kWh\ \ mo^{-1}] \tag{C.3.7}$$

Aggregate these to a an annual expectation with a confidence envelope:

$$\overline{\mathsf{AEY}} \ = \ \sum_{m=1}^{12}\overline{\mathsf{EY}}_m \quad [kWh\ \ yr^{-1}], \qquad \left[\sum_{m=1}^{12}\mathsf{EY}_m^{\mathsf{min}},\ \sum_{m=1}^{12}\mathsf{EY}_m^{\mathsf{max}}\right] \quad [kWh\ \ yr^{-1}] \tag{C.3.8}$$

Note: This captures typical seasonal structure by averaging each calendar month over years before summing to the annual figure.

D

Energy Appendix

D.1. Economic analyses

The methodology, equations and parameters used as input for the results in Table 5.3 will be explained in this part of the Appendix.

Table D.1: Input parameters for CAPEX and OPEX of solar and wind systems.

Entry	Value	Source	Comment
CAPEX Solar [USD]	(Redacted)	Premier Solar	Based on full system quotation; individual item prices not specified
PV-panels	–	Premier Solar	Includes 938 MN12R/132 solar panels
Inverters	–	Premier Solar	Includes 5, 125kW GROWATT Inverters
Mounting strucutes	–	Premier Solar	Includes mounting structures for rooftop and parking-lot solar installations
Materials	–	Premier Solar	Includes electrical material, screws, cables and pipes
Materials	–	Premier Solar	Includes electrical material, screws, cables and pipes
Labour	–	Permier Solar	Includes costs for engineering, installation and tender related costs
OPEX Solar [USD/year]	18,018	Premier Solar	Based on internal communication
Maintenance	–	Premier Solar	Three times per year
Cleaning	–	Premier Solar	Three times per year
Insurance	–	Premier Solar	Upgrade of current Campus insurrance
CAPEX Wind [USD]	112,168		
Aelos-V 5000W Turbine (5x)	82,168	(Krehenbrink, 2024)	Cost of each turbine: USD 16427
Installation costs	30,000	(Angi, 2024)	Construction, Grid connection, Transport
OPEX Wind [USD/year]	5,608		
Maintenance	1,122	Assumption	1% of the CAPEX
Spare parts	4,486	Assumption	4% of the CAPEX

Notes: CAPEX = Capital Expenditure; OPEX = Operational Expenditure. All values are expressed in nominal USD unless otherwise specified.

With this Return on Investment can be calculated (ROI) as follows:

$$\text{ROI}\ [\%] = 100 \times \frac{\sum_{t=0}^{N} \text{max}(CF_t, 0) - \left|\sum_{t=0}^{N} \text{min}(CF_t, 0)\right|}{\left|\sum_{t=0}^{N} \text{min}(CF_t, 0)\right|}. \tag{D.1.1}$$

$$\begin{aligned}
E_t &= E_1\,(1-\delta)^{\,t-1}, && t = 1,\ldots,N, && \text{(D.1.2)}\\
P_t &= P_1\,(1+\pi)^{\,t-1}, && t = 1,\ldots,N, && \text{(D.1.3)}\\
\text{OPEX}_t &= \text{OPEX}_1\,(1+\pi)^{\,t-1}, && t = 1,\ldots,N, && \text{(D.1.4)}\\
\text{Revenue}_t &= E_t\,P_t, && t = 1,\ldots,N, && \text{(D.1.5)}\\
CF_0 &= \text{CAPEX}, && && \text{(D.1.6)}\\
CF_t &= \text{Revenue}_t - \text{OPEX}_t, && t = 1,\ldots,N. && \text{(D.1.7)}
\end{aligned}$$

In this analyses the following assumptions are made, of which the values can be found in Table D.2:

- Lifetime is in accordance with information provided by manufacturer.
- OPEX and the electricity price escalate annually at the assumed inflation rate of 4% This inflation rate is based on the most conservative inflation target of Mexico's central bank (Reuters, 2025).
- Based on the analyses from Appendix B.
- Annual production degrades each year at the specified degradation rate from the PV module datasheet provide by Permier Solar. A similar degradation is assumed for Wind.
- The Electricity price from Year one is based on billing records from the CFE.

Table D.2: Key input parameters (symbols match the governing equations) used for the economic and energy analysis of solar PV and small-scale wind systems.

Parameter	[Unit]	Solar PV	Small-scale wind turbine
N lifetime	[year]	30	20
π inflation	[%/year]	4	4
E_1 annual production, Year 1	[kWh/year]	600,622	103,441
δ production degradation	[%/year]	0.5	0.5
P_1 electricity price, Year 1	[USD/kWh]	0.16	0.16

D.2. Reasoning of MCA

In this section, the individual solutions and their scores per criteria are motivated.

Table D.3: Multi-criteria scoring and reasoning for Solar PV installation at the Sisal campus.

Criterion	Score	Reasoning
CAPEX	5	High upfront investment required for large-scale installation.
OPEX	7	Requires periodic cleaning due to dust and salt exposure, moderate maintenance.
Durability/Lifespan	9	Panels last about 30 years with minimal degradation.
Resilience to Weather	9	Structurally suitable for local conditions, confirmed by Premier Solar.
Resilience to Flooding	10	Roof-mounted, therefore unaffected by flood risk.
Reliability During Outages	9	Very reliable as long as generated energy can be stored or supplied to users.
Energy Yield	8	Can supply up to 50% of campus demand depending on season.
CO_2 Reduction	8	Zero direct emissions, higher output than wind makes larger indirect reduction.
Land/Space Requirement	5	Large area needed, but rooftops and parking can be efficiently used.
Ecosystem Compatibility	8	Limited ecological impact, possible minor heat effect on birds.
Operational Complexity	7	Widely used technology, installation on roofs and parking adds some complexity.
User Acceptance (Campus)	7	Minimal interference, parking shade likely appreciated.
Community Involvement	6	Currently campus-focused, but easy to scale to local community later.

Table D.4: Multi-criteria scoring and reasoning for small-scale wind turbine installation at the Sisal campus.

Criterion	Score	Reasoning
CAPEX	7	Approx. 100k USD total investment, good return (about 7 year payback).
OPEX	8	Low maintenance, only periodic checks or repairs required.
Durability/Lifespan	7	Around 20 years of operational lifetime.
Resilience to Weather	8	Can withstand strong winds, requires solid foundation.
Resilience to Flooding	10	Roof-mounted, fully safe from flooding.
Reliability During Outages	9	Reliable energy supply when wind conditions are met.
Energy Yield	3	Contributes only 4–10% of total energy demand.
CO_2 Reduction	5	Renewable, but low output limits impact on overall emissions.
Land/Space Requirement	7	About 100 m^2 needed for five turbines, uses otherwise unused roof space. Low compared to solar. However, when scaled, much more space needed.
Ecosystem Compatibility	6	Bird-collision risk, vertical-axis design reduces impact.
Operational Complexity	8	Technically relatively simple, technology is widely used and installed, requires proper installation and foundation.
User Acceptance (Campus)	5	Slightly noisy and visually intrusive; may affect aesthetics.
Community Involvement	2	Not easily scalable, limited local benefit and visual impact could deter tourism.

E

Interviews

This appendix presents the conducted interviews and their corresponding file names. Each interview includes both the original transcript and an AI-enhanced version. Since the original recordings contained various language and spelling errors, an improved version was created to ensure better readability. This AI version is intended for content analysis only and should not be used for direct citation. The files are provided separately in a repository rather than included in this document, as their combined size would exceed the report's practical file limits.

Table (Redacted)

F

Water Appendix

The appendix of 6 is divided into two sections: water harvesting and water treatment. Each section follows the same structure. First, for each solution, a table is presented listing the input variables used to calculate the CAPEX, OPEX, Lifecycle, Potential Yield, and Surface Area. Next, the corresponding formulas used for these calculations are provided. Finally, for each solution, a table is included that explains and justifies the assigned values for each criterion used in the Multi-Criteria Analysis (MCA).

F.1. Water harvesting

F.1.1. Calculations

Solution 1: AC condensate harvesting

All parameters used as input for the calculation of CAPEX, OPEX, Yield and the tank base area and volume (Eqs. F.1.1–F.1.5) are listed in Table F.1.

Table F.1: Summary of all input parameters, values, and assumptions for AC condensate harvesting calculations.

Input / Parameter	Value	[Unit]	Source	Comments
Inputs: Yield				
Number of ACs in Faculty of Engineering	49.00	[dmnl]	Field testing	Only the number of AC units in the Faculty of Engineering building.
Number of ACs total	147.00	[dmnl]	Assumption	Estimated by multiplying the Faculty of Engineering's count by three (for three faculties).
Number of ACs on ($N_{\text{AC,on}}$)	73.50	[dmnl]	Assumption	Based on campus observations; not all rooms are occupied.
Average daily operating hours (h_{avg})	4.00	[hours/day]	Assumption	Corrective estimate, since not all ACs operate all day.
Operating days per year (d_{year})	240.00	[days/year]	Assumption	365 days minus 104 weekend days and 21 vacation days.
Yield (Y_{coef})	0.92	[L/h/AC]	(Okeyinka et al., 2021)	Average condensate yield per AC unit under typical tropical conditions.
Inputs: CAPEX				
Pipes (C_{pipes})	3,000.00	[USD]	Assumption	Estimated from local PVC piping costs of 8–12 USD/m including fittings and labor.
Valves (C_{valves})	1,000.00	[USD]	Assumption	Based on three main manifolds with ball valves and check valves.
Pre-filter ($C_{\text{pre-filter}}$)	400.00	[USD]	Assumption	Market prices for 10–20″ cartridge filters; includes first set of cartridges.
pH management (C_{pH})	600.00	[USD]	Assumption	Cost of a small pressure vessel (30–40 L) with 25 kg calcite media.
Desinfection ($C_{\text{desinfection}}$)	1,000.00	[USD]	Assumption	Based on small-scale UV units or chlorination kits with dosing pump.

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Table F.1 Continued from previous page

Input / Parameter	Value	Unit	Source	Comments
Tank (C_{tank})	1,800.00	[USD]	Assumption	Average supplier price of 600–900 USD per tank including delivery.
Pump (C_{pump})	500.00	[USD]	Assumption	Market price for light-duty centrifugal pump with basic fittings.
Meters (C_{meter})	500.00	[USD]	Assumption	Based on low-cost inline flow sensors and float switches.
Installation & contingency ($C_{\text{installation}}$)	1,800.00	[USD]	Assumption	Estimated at 25–30% of total equipment cost for small systems.
Inputs: OPEX				
Electricity ($C_{\text{electricity}}$)	60.00	[USD]	Assumption	Based on a 40 W UV unit operating 10 h/day and a 0.4 kW pump for 2 h/day, 300 days per year.
Filter cartridges ($C_{\text{filter cartridges}}$)	200.00	[USD]	Assumption	Market price for sediment and activated-carbon cartridges plus calcite top-ups.
UV lamp replacements ($C_{\text{UV lamp}}$)	80.00	[USD]	Assumption	Typical UV lamp rated for 8,000–9,000 hours.
Labor & inspection (C_{labor})	200.00	[USD]	Assumption	Periodic cleaning, checking flow, and replacing filters.
Miscellaneous (hoses, cleaning) ($C_{\text{miscellaneous}}$)	100.00	[USD]	Assumption	Allowance for minor parts and maintenance materials.
Inputs: Lifecycle				
Piping / tanks	15.00	[years]	Assumption	Durable PVC and polyethylene materials; minimal degradation under UV protection.
Pumps	7.00	[years]	Assumption	Based on manufacturer data for light-duty centrifugal pumps; periodic maintenance expected.
UV reactor body	10.00	[years]	Assumption	Stainless or polymer housing with proper maintenance; occasional quartz sleeve replacement.
Filter media	1.00	[years]	Assumption	Sediment or activated-carbon cartridges replaced regularly to maintain quality.
Inputs: Surface Area				
Diameter (D)	0.83	[m]	–	Calculated tank diameter to achieve required storage volume.
Volume (V)	360.64	[L/day]	–	Potential yield per building if all 47 ACs operate 8 hours/day.
Volume with redundancy	540.96	[L]	–	150% of maximum daily yield to include storage margin.
Height (H)	1.00	[m]	–	Typical small vertical tank height.
Base area (A_{base})	0.54	[m^2]	–	Calculated using $\pi \times (D/2)^2$.
Amount of tanks	3.00	[dmnl]	Assumption	Each faculty assumed to have one independent tank.

Eq. F.1.1 was developed to calculate the annual condensate yield. Field observations showed that the

Faculty of Engineering contains 49 air conditioning (AC) units. It was assumed that the campus has a total of 147 AC units, of which approximately half operate simultaneously. These units are estimated to function for half of an average working day (4 hours) over 240 working days per year. The yield coefficient applied in this calculation was obtained from Okeyinka et al., 2021. Eqs. F.1.2–F.1.5 represent the summation of all cost components and the calculations used to determine the tank volume and base area.

$$Y_{\text{year}} = Y_{\text{coef}} \times N_{\text{AC,on}} \times h_{\text{avg}} \times d_{\text{year}} \tag{F.1.1}$$

$$\text{CAPEX} = C_{\text{pipes}} + C_{\text{valves}} + C_{\text{pre-filter}} + C_{\text{pH}} + C_{\text{desinfection}} + C_{\text{tank}} + C_{\text{pump}} + C_{\text{meter}} + C_{\text{installation}} \tag{F.1.2}$$

$$\text{OPEX} = C_{\text{electricity}} + C_{\text{filter cartridges}} + C_{\text{UV lamp}} + C_{\text{labor}} + C_{\text{miscellaneous}} \tag{F.1.3}$$

$$V = \pi \left(\frac{D}{2}\right)^2 H \tag{F.1.4}$$

$$A_{\text{base}} = \pi \left(\frac{D}{2}\right)^2 \tag{F.1.5}$$

Solution 3: Rainwater harvesting
All parameters used as input for the calculation of CAPEX, OPEX, and potential yield (Eqs. F.1.6–F.1.8) are listed in Table F.2.

Table F.2: Summary of input parameters, values, and assumptions for the rainwater harvesting system at the Sisal campus.

Input / Parameter	Value	Unit	Source	Comments
Inputs: Yield				
Yield coefficient concrete (Y_{conc})	0.70	[Dmnl]	Bektas	A value of 0.70 chosen within 0.60–0.80 range.
Yield coefficient polymer (Y_{poly})	0.85	[Dmnl]	Bektas	For polymer roofs 0.85 chosen (range 0.8–0.9).
Quantity of precipitation (P_{avg})	488	[L/m^2/year]	(WeatherSpark, 2025)	Average yearly rainfall.
Inputs: CAPEX				
Gutters & downpipes (C_{gutters})	4,000	[USD]	Estimate	Based on $\sim$6,000 m^2 roof drainage consolidation; includes leaf screens.
First-flush diverters ($C_{\text{first-flush}}$) & debris screens	1,200	[USD]	Estimate	For primary roof lines, sized for tropical rains.
Filtration (sediment + cartridge) ($C_{\text{filtration}}$)	1,000	[USD]	Vendor ballpark	Two-stage housings (20″) incl. initial cartridges.
Disinfection (UV or chlorination) ($C_{\text{disinfection}}$)	1,200	[USD]	Vendor ballpark	Small UV unit or chlorine dosing kit (non-potable end uses).
Storage tanks ($\approx$ 50 m^3 total) (C_{storage})	8,000	[USD]	Market	Two poly tanks $\sim$25 m^3 each incl. delivery/pads.
Transfer/booster pump set (C_{pump})	1,200	[USD]	Market	One 0.75–1.1 kW pump with controller.
Piping, valves, meters, controls (C_{piping})	2,200	[USD]	Estimate	Header, isolation valves, flow meter, level switch.
Installation & contingency ($C_{\text{installation}}$)	4,700	[USD]	Rule of thumb	Civil base, plumbing/electrical, 10% contingency included.

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Table F.2 Continued from previous page

Input / Parameter	Value	[Unit]	Source	Comments
Inputs: OPEX				
Electricity (pump + UV) ($C_{\text{electricity}}$)	180	[USD/year]	Estimate	∼1,200 kWh/yr × 0.15 USD/kWh (intermittent pumping).
Cartridge filters (C_{filters})	150	USD/year	Market	Two 20″ replacements/yr.
UV lamp or chlorine consumables ($C_{\text{UV/chlorine}}$)	90	[USD/year]	Market	One lamp/yr or chlorine + test kits.
Minor parts/cleaning (C_{cleaning})	80	[USD/year]	Allowance	Hoses, screens, sealants.
Routine maintenance labor (C_{labor})	240	[USD/year]	Assumption	∼30 h/yr × 8 USD/h.
Water quality monitoring ($C_{\text{monitoring}}$)	120	[USD/year]	Allowance	Periodic lab checks for non-potable reuse.
Meter calibration/servicing ($C_{\text{calibration}}$)	40	[USD/year]	Allowance	Annual check.
Contingency ($C_{\text{contingency}}$)	100	[USD/year]	Allowance	Small unforeseen O&M.
Inputs: Lifecycle				
Gutters/downpipes	20	[years]	Assumption	With periodic cleaning and anti-corrosion fixings.
Storage tanks (polyethylene)	20	[years]	Vendor typical	UV-stabilized; inspect vents/overflows annually.
Pump	8	[years]	Vendor typical	Mid-life seal/impeller service expected.
UV reactor body / chlorination skid	10	[years]	Vendor typical	UV lamp yearly; chlorine pump tubing 1–2 yr.
Cartridge filters	0.5	[years]	Practice	Replace every 6–12 months depending on load.
Flow meters/sensors	10	[years]	Vendor typical	Non-aggressive water; periodic calibration.
Control panel	12	[years]	Vendor typical	Replace relays/pressure switch as needed.
Civil pads/stands	25	[years]	Assumption	Concrete base for tanks/pumps.
Inputs: Surface Area				
Engineering building (A_{Eng})	1,286	[m^2]	Google Maps	Measured using Google satellite imagery.
Chemistry building (A_{Chem})	2,189	[m^2]	Google Maps	Measured using Google satellite imagery.
Marine biology building (A_{Bio})	815	[m^2]	Google Maps	Measured using Google satellite imagery.
Cafeteria (A_{Caf})	610.55	[m^2]	Google Maps	Measured using Google satellite imagery.
Unidad Multidisciplinaria (A_{UM})	1,171	[m^2]	Google Maps	Measured using Google satellite imagery.

Eq. F.1.1 was developed to calculate the annual potential rainwater yield. Using Google Maps, a rough estimation of roof surface area was made for each cluster of buildings. The Unidad Multidisciplinaria is equipped with polymer roofs; therefore, a different yield coefficient was applied. The yield coefficients were obtained from Bektas et al., 2017. The average annual precipitation was derived from open-source climate data (WeatherSpark, 2025) and multiplied by the sum of the roof surface areas, each weighted by its corresponding yield coefficient. Eqs. F.1.7–F.1.8 represent the summation of all cost components.

$$\text{Potential Yield} = P_{\text{avg}} \times \Big[(Y_{\text{conc}} \times (A_{\text{Eng}} + A_{\text{Chem}} + A_{\text{Bio}} + A_{\text{Caf}})) + (Y_{\text{poly}} \times A_{\text{UM}})\Big] \tag{F.1.6}$$

$$\text{CAPEX} = C_{\text{gutters}} + C_{\text{first-flush}} + C_{\text{filtration}} + C_{\text{disinfection}} + C_{\text{storage}} + C_{\text{pump}} + C_{\text{piping}} + C_{\text{installation}} \tag{F.1.7}$$

$$\text{OPEX} = C_{\text{electricity}} + C_{\text{filters}} + C_{\text{UV/chlorine}} + C_{\text{cleaning}} + C_{\text{labor}} + C_{\text{monitoring}} + C_{\text{calibration}} + C_{\text{contingency}} \tag{F.1.8}$$

F.1.2. Reasoning of MCA

In this section, the individual solutions and their scores per criteria are motivated.

Solution 1: AC condensate harvesting

Table F.3: Multi-criteria scoring and motivation for AC condensate harvesting at the Sisal campus.

Criterion	Score	Reasoning
Capex	9	The installation requires only simple piping and small storage tanks connected to existing AC units, resulting in very low initial investment costs.
Opex	9	Operating costs are minimal, as the system requires little maintenance beyond occasional cleaning of filters and tanks.
Durability/lifespan	6	Tanks and pipes last long, but AC units require regular replacement; dependency on AC lifetime.
Yield	5	The annual water yield is relatively low and directly dependent on the number of active AC units and their operating hours.
Land/space requirements	9	Requires very little space; only small tanks are needed.
Resilience weather	7	Collection tanks are robust, but AC units may fail under hurricanes or prolonged power interruptions.
Resilience floodings	7	Elevated or protected tanks and piping can resist moderate floods, but are vulnerable if flooding damages infrastructure.
Reliability outages	5	Entirely dependent on AC operation; during outages, no condensate is produced.
Periods of drought	8	In drier periods temperatures in Sisal remain high, so AC demand persists and condensate is produced year-round.
High salinity	10	Independent of groundwater or seawater salinity, since the source is atmospheric humidity.
Energy consumption	9	Uses waste condensate from existing AC energy demand; negligible additional energy consumption.
CO_2 savings	6	Reduces dependency on trucked water, lowering transport-related emissions, but savings are limited by small volumes.
Water quality	7	The condensate is comparable to distilled water but may contain traces of metals or acids from corroded cooling coils.
Ecosystem compatibility	7	Neutral to slightly positive: reduces water trucking and plastic waste but overall environmental impact is limited.
Operational complexity	8	Simple system; requires minimal training or oversight once installed.
User acceptance campus	8	Likely to be accepted as low-cost and visible; quality concerns might limit enthusiasm for potable use.
Community involvement	6	Limited direct community impact, though reduced trucking may indirectly benefit local environment and logistics.

Solution 2: Small-scale desalination

Table F.4: Multi-criteria scoring and motivation for desalination at the Sisal campus.

Criterion	Score	Reasoning
Capex	5	The installation requires a high initial investment due to the need for membranes, pumps, possibly photovoltaic (PV) integration and technical housing.
Opex	5	Operational costs are high because of electricity use, membrane cleaning, and replacement, but remain manageable when powered by solar energy and supported with basic maintenance training.
Durability/lifespan	8	Membranes last 5–7 years, system 20–25 years with proper maintenance; long-term viability.
Yield	9	The system can reliably produce a consistent volume of high-quality water independent of rainfall, with the potential to meet most or all of the campus's water demand if adequately scaled.
Land/space requirements	7	Requires technical rooms and PV panels; more land than AC but less than large rainwater storage.
Resilience weather	8	RO units can be sheltered; PV panels are generally resistant but vulnerable to hurricane-force winds.
Resilience floodings	7	Units can be elevated and protected, but flooding risks damaging electrical components.
Periods of drought	9	Independent of rainfall; continuous supply as long as seawater or brackish water is available.
High salinity	9	RO is designed for seawater and brackish water; high salt rejection (>99%).
Energy consumption	3	Requires pressurization (up to 55 bar for brackish water, higher for seawater); energy-intensive.
CO_2 savings	8	Significant reduction if powered by PV, as it avoids diesel-based transport from Mérida and it avoids pumping from the aquifer.
Water quality	9	The produced water meets potable standards with over 99% salt rejection through reverse osmosis, providing a stable and high-quality source suitable for drinking when properly monitored.
Ecosystem compatibility	6	Potential brine disposal risk if mismanaged; positive impact if it reduces aquifer over-extraction.
Operational complexity	6	Requires skilled operators for membrane monitoring, cleaning, and troubleshooting. However, EWM train people to do operations and have a direct troubleshoot line.
User acceptance campus	6	Potable water quality encourages acceptance, but awareness of costs and complexity may raise concerns.
Community involvement	7	Could provide potable water security beyond campus if scaled; may serve as demonstration project for Sisal.

Solution 3: Rainwater harvesting

Table F.5: Multi-criteria scoring and motivation for rainwater harvesting at the Sisal campus.

Criterion	Score	Reasoning
Capex	8	Investment costs are relatively low, as the system mainly requires gutters, piping, filters, and storage tanks; however, costs can increase if roofs are unsuitable or additional structures are needed for collection.
Opex	8	Operational expenses are minimal since the system operates largely by gravity, with maintenance limited to occasional cleaning of tanks, filters, and collection surfaces.
Durability/lifespan	8	Tanks and infrastructure can last 20+ years if maintained; filters require periodic replacement.
Yield	7	TThe potential yield is high, covering an estimated 15% of annual demand; expansion is possible by integrating additional catchment areas such as parking structures.
Land/space requirements	4	Large storage tanks occupy space; significant requirement compared to AC or desalination.
Resilience weather	6	Tanks are resistant, but gutters and collection systems may be damaged by storms.
Resilience floodings	5	Ground-level tanks can be damaged or contaminated during flooding events.
Reliability outages	9	Gravity-fed distribution possible; does not depend on electricity.
Periods of drought	3	Strongly dependent on rainfall; limited reliability during prolonged dry seasons.
High salinity	5	Not affected by groundwater salinity, but rooftop dust/salt spray near the coast can reduce quality.
Energy consumption	8	Minimal energy demand; primarily gravity-based.
CO_2 savings	8	Reduces water trucking from Mérida, lowering transport emissions.
Water quality	6	With proper filtration and disinfection, the harvested rainwater is suitable for non-potable uses and potentially for drinking; however, quality varies due to possible contamination from debris, bird droppings, or sea spray on rooftops.
Ecosystem compatibility	8	Benefits ecosystems by reducing aquifer extraction and runoff impacts; minimal risks if properly managed.
Operational complexity	7	Installation moderately complex; monitoring and maintenance relatively simple.
User acceptance campus	8	Familiar and visible; aligns with sustainability goals; likely to be well received.
Community involvement	8	Demonstrates sustainable practices; potential to extend knowledge and benefits to Sisal households.

F.2. Water treatment

F.2.1. Calculations

All parameters used as input for the calculation of the values in Table 6.3.

Solution 1 and 2:

Table F.6: Final baseline parameters and assumptions for CAPEX, OPEX, and surface area scaling.

Parameter	Value	Unit	Source	Comments
Inputs: Baseline and Design Parameters				
Baseline flow for scaling	20	[m^3/d]	(Sagastume, 2022)	Report baseline for cost scaling
Nominal module capacity	4	[m^3/d]	Report assumption	Single micro-plant nominal size used in report examples

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Table F.6 Continued from previous page

Parameter	Value	[Unit]	Source	Comments
Inputs: CAPEX and OPEX Baselines				
Centralized CAPEX @ baseline	2,100,000	[MXN] (excl. VAT)	(Sagastume, 2022)	Centralized estimate for $\sim$20 m^3/d
Decentralized CAPEX @ baseline	3,000,000	[MXN] (excl. VAT)	(Sagastume, 2022)	Based on $\approx$5 modules
Centralized OPEX	8.00	% of CAPEX (excl. VAT)	Planning assumption	Linear with CAPEX excl. VAT
Decentralized OPEX	10.00	% of CAPEX (excl. VAT)	Planning assumption	Linear with CAPEX excl. VAT
Life cycle	25	years	Industry average	Common assumption for biological treatment units
Inputs: Surface Area Requirements				
Surface area for 45 m^3/d	350	[m^2]	(Özdemir & Sengorur, 2006)	Literature reference for constructed wetland sizing
Surface area for 20 m^3/d	155	[m^2]	Calculated	Scaled proportionally from 45 m^3/d reference

Solution 3:

Table F.7: Parameters and assumptions for BIOBOX Organic Matter MBBR system (20 m^3/d baseline).

Parameter	Value	[Unit]	Source	Comments
Inputs: Baseline and Design Parameters				
Baseline flow for scaling	20	[m^3/d]	(Sagastume, 2022)	Average daily wastewater discharge from campus
Module nominal capacity	20	[m^3/d]	(BIOBOX Water, 2023)	Modular containerized system
Inputs: CAPEX and OPEX Baselines				
CAPEX @ 20 m^3/d baseline	115k	[USD] (excl. VAT)	(Yang et al., 2020)	Capex of a typical MBBR system
OPEX @ 300 mg/L BOD_5	2,190	[USD/year]	(BIOBOX Water, 2023)	Based on OPEX ≈ 0.10 €/m^3 per 100 mg/L BOD_5 removed (converted to USD @ 1.10 EUR/USD)
Life cycle	25	[years]	Industry average	Common assumption for biological treatment units
Inputs: Surface Area Requirements				
Surface area (20 ft container)	14.8	[m^2]	ISO standard container dimensions (6.06 × 2.44 m)	Approximate needed surface area of one module
Calculated / Derived Values				
Annual flow	7,300	[m^3/year]	Calculated	20 m^3/d × 365 days
OPEX per m^3 treated	0.30	[EUR/m^3]	(BIOBOX Water, 2023)	For BOD_5 ≈ 300 mg/L domestic wastewater

F.2.2. Reasoning of MCA

In this section, the individual solutions and their scores per criteria are motivated.

Table F.8: Criteria reasoning for Water Treatment Solution 1: Centralized Subsurface Constructed Wetland.

Criterion	Score	Reasoning
CAPEX	7	Moderate investment for one large wetland system with simple construction and limited mechanical parts.
OPEX	6	Low yearly cost but requires periodic vegetation management and solids removal.
Lifespan	7	Can operate for decades if maintained properly with vegetation replacement when needed.
Resilience weather	6	Sensitive to strong winds and heavy rain which can damage vegetation and affect treatment.
Resilience flooding	6	Must be elevated about one meter to avoid inundation which is difficult due to large needed surface area.
Energy consumption	8	Operates mostly by gravity and biological processes with very low energy demand.
CO_2 reduction	6	Produces natural CO_2 and methane through biological degradation similar to current system.
Water reuse potential	6	Effluent suitable for reuse after disinfection though not designed primarily for that purpose.
Water quality	7	Meets NOM-001 limits for BOD and nutrients with consistent effluent quality when maintained.
Total water treatment	6	Can handle the full campus load under normal conditions but less flexible under variable flow.
Land usage	3	Requires large surface area compared to other systems which limits flexibility on campus.
Risk of harming the ecosystem	8	Minimal risk and can even support local biodiversity when well designed.
Complexity of operating solution	7	Technically simple but requires attention to vegetation and occasional solids management.
Likely acceptance	6	Acceptable for most users though odor and visual exposure might limit perception of cleanliness.
Community benefits and involvement	5	Indirect benefits through improved groundwater but limited community engagement or awareness.

Table F.9: Criteria reasoning for Water Treatment Solution 2: Decentralized Subsurface Constructed Wetlands.

Criterion	Score	Reasoning
CAPEX	6	Higher investment due to the need for multiple smaller wetland units and separate infrastructure.
OPEX	5	Higher operational cost compared to the centralized system since several units need individual maintenance.
Lifespan	7	Similar lifespan to the centralized wetland when maintained, with the benefit of phased replacement per module.
Resilience weather	6	Exposed to wind, rainfall, and salt air, which can stress vegetation across different sites.
Resilience flooding	6	Each wetland needs to be elevated and lined, which increases construction effort and cost.
Energy consumption	8	Operates passively with low energy demand, although some pumping may be required between clusters.
CO_2 reduction	6	Emits CO_2 and methane through natural biological degradation similar to other wetland systems.
Water reuse potential	6	Effluent can be reused after filtration or disinfection, though not the main system goal.
Water quality	7	Meets NOM-001 standards with good performance but some variation between units is expected.
Total water treatment	6	Capable of handling all campus wastewater when distributed effectively across clusters.
Land usage	4	Requires smaller plots spread across campus instead of one large site, improving flexibility but still space-intensive overall.
Risk of harming the ecosystem	8	Low environmental risk and can provide ecological value if integrated with green areas.
Complexity of operating solution	6	More complex to maintain due to several decentralized systems needing regular supervision.
Likely acceptance	6	Generally accepted, though visibility and odor near localized wetlands might reduce comfort.
Community benefits and involvement	5	Indirect positive impact through cleaner discharge and groundwater but limited direct community interaction.

Table F.10: Criteria reasoning for Water Treatment Solution 3: BIOBOX MBBR system.

Criterion	Score	Reasoning
CAPEX	7	Moderate investment for a compact and prefabricated system with higher unit cost offset by easy installation.
OPEX	8	Very low operating cost at around 2.19 k USD/year due to automation, limited maintenance, and low energy use.
Lifespan	7	Typical 25-year lifespan for modular biological units with easily replaceable components.
Resilience weather	9	Fully enclosed container protected from strong winds, rain, and salt exposure.
Resilience flooding	8	Compact and modular, easily elevated above flood level or relocated when needed.
Energy consumption	6	Requires moderate power for pumping and control but remains efficient compared to conventional systems.
CO_2 reduction	6	Emits similar CO_2 levels to other biological systems through natural degradation.
Water reuse potential	8	Produces high-quality effluent suitable for reuse after basic disinfection.
Water quality	8	Consistently meets NOM-001 limits with effluent below 25 mg/L BOD_5 and strong nutrient removal.
Total water treatment	8	Handles the full 20 m^3/d campus load with reliable and predictable treatment performance.
Land usage	9	Minimal surface area, fitting within a standard shipping container and requiring little on-site space.
Risk of harming the ecosystem	9	Enclosed system prevents discharge risks and minimizes interaction with surrounding environment.
Complexity of operating solution	8	Automated control reduces daily workload though technical supervision is still needed.
Likely acceptance	8	Clean and odor-free installation that is easy to integrate within the campus environment.
Community benefits and involvement	5	Indirect community benefit through cleaner groundwater but no direct local involvement.

G

Waste Appendix

Reasoning of MCA

In this Appendix, the individual solutions and their scores per criteria are motivated.

Table G.1: Criteria reasoning for Waste Solution 1

Criterion	Score	Reasoning
Capex	9	Very low investment (mostly bins, signage, awareness).
Opex	8	Costs rely on participation & NGO partnership; costs are low but coordination requires some ongoing effort.
Durability/lifespan	8	System is simple and long-lasting if local community keeps participating.
Resilience weather	9	Collection/composting bins are independent, unless outside but easily replaced. Only transportation might be hindered.
Resilience floodings	9	Collection/composting bins are independent, unless outside but easily replaced. Only transportation might be hindered.
Circularity	7	Promotes composting + recycling; high circularity but limited to organic and easy recyclables, weaker for complex waste streams.
Pollution reduction	9	100% diversion of organic waste + 27% recyclables diverted in case study. Plus community involved so no mangrove waste.
Waste diversion	8	Very strong, diverts all organics and much of recyclables (depends on what NGO can collect). No specific numbers to verify.
CO_2 savings	7	Avoids methane from landfills + reduces transport emissions (very little though).
Land/space requirements	9	Minimal; bins and small compost area.
Ecosystem compatibility	9	Strongly positive, prevents landfill leakage and mangrove dumping.
Operational complexity	6	Requires coordination and education; technically simple but organizationally sensitive, especially with local community (NGO's).
User acceptance campus	9	Fits student/academic context well; relies on consistent awareness.
Community involvement	9	Strength is high NGO/community involvement; case study showed strong social benefits.

Table G.2: Criteria reasoning for Waste Solution 2

Criterion	Score	Reasoning
Capex	7	Requires bins, composting area, and some infrastructure. Higher than Zero Waste grassroots but still moderate.
Opex	6	Needs staff/coordination to maintain composting system. Costs are higher than a grassroots model but still reasonable.
Durability/lifespan	9	Has been operating since 2014; strong if institutional support is present.
Resilience weather	8	Composting areas may be vulnerable to heavy rain; mitigation (covering, drainage) is needed.
Resilience floodings	8	Composting areas may be vulnerable to flooding; mitigation (covering, drainage) is needed.
Circularity	8	Multi-stream system handles organics + recyclables (paper, metals). Strong closed-loop potential because of self recycling structure.
Pollution reduction	8	In 2017, 90% of food waste and 100% of garden waste composted; significant reduction of landfill waste. Chemical waste?
Waste diversion	8	8 tons/year recycled (in case study) + composting diversion but not 100% of all campus waste. More categories than solution 1, however means more chance on leak.
CO_2 savings	7	Avoids methane from landfill organics, reduces transport emissions, but not as impactful as energy recovery tech.
Land/space requirements	7	Needs designated compost space; feasible but larger than grassroots model.
Ecosystem compatibility	8	Strong positive effect; avoids dumping in sensitive ecosystems like mangroves.
Operational complexity	5	More complex than grassroots: multi-streams, compost management, staff training + unclear where to bring the waste that is not treated on campus?
User acceptance campus	7	Proven success at another UNAM campus; requires buy-in but well suited to a university context.
Community involvement	2	Mostly campus-internal. No clear direct benefit to outside community.

Table G.3: Criteria reasoning for Waste Solution 3

Criterion	Score	Reasoning
Capex	9	Very low investment, only bins/boxes and awareness materials (posters, stickers).
Opex	8	Low operating costs, but requires coordination and monitoring (students need to be organized). Possibly costs for recycle company partner.
Durability/lifespan	6	Works well while students are engaged, but participation may drop during breaks/holidays or if new generation of students not so engaged anymore.
Resilience weather	9	Collecting is indoors, only trouble with pickup/transportation to recycling point.
Resilience floodings	9	Collecting is indoors, only trouble with pickup/transportation to recycling point.
Circularity	8	Closed-loop potential because of self recycling structure. However the recycling itself is given to other party, so depends on what they do with the waste.
Pollution reduction	8	Reduces waste sent to landfill, but depends on recycling company.
Waste diversion	7	Diverted 6 tons of paper and cardboard in 16 months; solid but limited in scope. However, this is just paper, if applied to all wastestreams could get even higher diversion rate.
CO_2 savings	7	Avoids methane from landfill organics, reduces transport emissions, but not as impactful as energy recovery tech.
Land/space requirements	9	Minimal, just collection boxes and main collection area for students to bring the waste to.
Ecosystem compatibility	8	Strong positive effect; avoids dumping in sensitive ecosystems like mangroves.
Operational complexity	5	Simple logistics, but highly dependendt on voluntary participation and recycle companies willing to pick up the waste.
User acceptance campus	9	Very high; students rated it “easy and convenient.”
Community involvement	3	Strong campus participation, but limited spillover into the wider community. However, could be easy to implement.

Table G.4: Criteria reasoning for Waste Solution 4

Criterion	Score	Reasoning
Capex	3	This solution requires expensive industrial-scale pyrolysis equipment. It's considered capital intensive and may exceed the available campus budget. However, small-scale pilot units do exist (e.g., at Ewha Womans University), and with institutional support or partnerships, implementation is not entirely out of reach.
Opex	3	Maintenance and energy inputs for pyrolysis are significant. The process requires ongoing technical support and reliable operations.
Durability/lifespan	8	If well maintained, pyrolysis systems can last long (10+ years), which is comparable to or better than traditional equipment.
Resilience weather	9	As an indoor industrial system, it can be sheltered from rain and wind
Resilience floodings	7	Depends on siting. If placed in a flood-safe zone or on elevated platforms, risk is manageable. Otherwise, performance could be disrupted.
Circularity	8	Strong closed-loop potential: it turns plastic waste into usable fuel. However, limited to plastic waste only.
Pollution reduction	7	Reduces waste (just plastic) going to landfills or open dumping. However, it does emit (non) greenhouse gases (though mostly below legal limits) and must be managed properly.
Waste diversion	7	If implemented properly and scaled up, could process significant plastic waste volumes. However limited to plastic.
CO_2 savings	5	Depends on comparison baseline. Could reduce methane emissions from plastic waste in landfills, but the process itself also emits CO□.
Land/space requirements	6	Requires space for industrial setup, likely larger than composting or bin-separation systems. Could be challenging for the campus scale.
Ecosystem compatibility	7	Medium risk. If handled improperly (e.g. toxic leakage), could harm ecosystems. If managed well, can reduce landfill and protect mangroves.
Operational complexity	3	Technically demanding. Needs trained staff, regular monitoring, and industrial knowledge
User acceptance campus	3	Not student-facing or participatory. Low direct involvement. Harder to engage students or raise awareness compared to more visible methods.
Community involvement	5	If local waste pickers or community members can be involved in collecting plastic, it could offer economic benefit. Otherwise, benefits are limited to indirect pollution reduction.

Table G.5: Criteria reasoning for Waste Solution 5

Criterion	**Score**	**Reasoning**
Capex	5	Basic small-scale AD units (200L) are relatively low-cost and low-tech compared to solution 5, but more costs than for example compost area solution 2. Construction, plumbing, and basic equipment needed.
Opex	6	Requires daily monitoring and minor upkeep (pH, temperature, water mixing). Costs are moderate but manageable for university staff or students.
Durability/lifespan	7	If well maintained, AD units can last 5–10 years. Simple design, few moving parts.
Resilience weather	9	Installed indoor or under cover, it can be sheltered from rain and wind.
Resilience floodings	8	Can be elevated; tanks are sealed. Can operate above flood level, but long-term exposure to moisture should be managed.
Circularity	8	Excellent. Creates closed loop: food waste → energy + fertilizer. Fully fits reuse and waste recovery goals. However, limited to organic waste only.
Pollution reduction	7	Removes up to 95% of COD/BOD. Strong reduction in organic pollution; better than composting. However, limited to organic waste only.
Waste diversion	8	Each 1 kg food waste → 67L biogas. With 12,750 kg/year = major diversion. However, limited to organic waste only.
CO$_2$ savings	8	Avoids methane emissions from rotting food, replaces 30 LPG tanks or 1,780 kWh electricity.
Land/space requirements	8	Small footprint (2–3 m^2 per tank). Very compact compared to pyrolysis or composting.
Ecosystem compatibility	7	Medium risk. If handled improperly (e.g. toxic leakage), could harm ecosystems. If managed well, can reduce landfill and protect mangroves.
Operational complexity	4	Requires basic training for monitoring, but no complex tech or industrial equipment. However, it requires a consistent supply of organic waste and carefully controlled conditions—such as temperature, pH, and nutrient balance—to maintain stable microbial activity and efficient biogas production.
User acceptance campus	6	Students unlikely to interact directly; if staff runs it (e.g. canteen), easier. Not highly visible. However they need to be aware to seperate organic waste.
Community involvement	3	Mostly campus-internal. No clear direct benefit to outside community unless scaled (scaling is possible).

H

Surveys

H.1. Multi-Criteria Analysis Surveys

This appendix section contains the collated responses from the Multi-Criteria Analysis (MCA) weighting survey. This survey was based on a list of sustainability criteria developed and iterated upon in consultation with the project supervisor, Alec Torres. After finalizing the criteria, the survey was distributed to determine the quantitative weightings for each, based on stakeholder input (Table H.1).

Table H.1: MCA survey file

#	Survey Name	Description	File Name
1	MCA Weighting Survey	Collated responses for weighting sustainability criteria	MCA Weighting Responses.pdf

H.2. Student Surveys

This appendix section contains the collated responses from the student survey conducted on campus. The survey was originally administered in Spanish, and the complete set of responses was subsequently translated into English to ensure better readability and for content analysis (Table H.2).

Table H.2: Student survey files and their translations

#	Survey Name	Description	Original File Name	Translated File Name
1	Student Survey	Collated responses regarding sustainability on campus	Student Survey Responses - Spanish.pdf	Student Survey Responses - English.pdf