Development of a Sustainable Community in the Ayoreo community of Campo Loro: Designing a solar PV water pumping and treatment system as part of a Goodwill Action

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Abstract

English

We are at a time when work towards sustainable development and eradication of multidimensional poverty is widespread through the UN Sustainable Development Goals. However, results are lukewarm, and inequality is on the rise. This is especially true for the Ayoreo indigenous people of the Gran Chaco, who frequently lack access to secure land tenure and are disproportionately affected by multidimensional poverty and massive deforestation in their territory. In the Ayoreo community of Campo Loro, Boquerón, Paraguay, this multidimensional poverty is currently reflected in potable water scarcity. This study provides the methodology and results for the initial design of a PV-powered water pumping and treatment system that covers the community's estimated daily potable water consumption of 10 m^3. The design is performed in the context of the development of a Goodwill Action in Campo Loro, with hopes of it evolving into a Sustainable Community Project. The obtained system is composed by 52 solar panels, an electrodialysis reversal desalination system, an electrochemical disinfection unit, a submersible groundwater pump, and three water tanks of 65 m^3, 10 m^3, and 10 m^3.

Galician

Actualmente vivimos nunha época de traballo intenso e xeneralizado cara o desenvolvemento sustentable e a erradicación da pobreza a través dos Obxectivos de Desenvolvemento Sustentable da ONU. Porén, os resultados acadados ata agora son moderados e a desigualdade medra. Esta situación é especialmente visible na poboación indíxena ayoreo do Gran Chaco, que acotío non ten acceso a unha tenencia segura da terra e vese desproporcionadamente afectada pola pobreza multidimensional e pola deforestación masiva á que se somete o seu territorio. Na comunidade ayoreo de Campo Loro, en Boquerón, Paraguai, esta pobreza multidimensional reflíctese principalmente na escaseza de auga potable. Este traballo describe a metodoloxía e resultados obtidos para o deseño inicial dun sistema de bombeo e tratamento de auga alimentado por enerxía solar fotovoltaica, que logra cubrir os 10 m^3 de consumo diario estimado de auga potable da comunidade. Este deseño realízase como parte do desenvolvemento dunha Acción de Boa Vontade en Campo Loro, coa posibilidade de transformarse nun Proxecto de Comunidade Sustentable. O sistema obtido componse de 52 paneis solares, unha unidade de desalinización de electrodiálisis reversible, unha unidade de desinfección electroquímica, unha bomba somerxible para a auga subterránea e tres tanques de auga de 65 m^3, 10 m^3 e 10 m^3.

Spanish

Actualmente vivimos en una época de trabajo intenso y generalizado cara al desarrollo sostenible y la erradicación de la pobreza a través de los Objetivos de Desarrollo Sostenible de la ONU. Sin embargo, los resultados recabados hasta ahora son moderados y la desigualdad va en aumento. Esta situación es especialmente visible en la población indígena ayoreo del Gran Chaco, que frecuentemente no tiene acceso a una tenencia segura de la tierra y se ve desproporcionalmente afectada por pobreza multidimensional y por la deforestación masiva a la que se somete su territorio. En la comunidad ayoreo de Campo Loro, en Boquerón, Paraguay, esta pobreza multidimensional se refleja principalmente en una escasez de agua potable. Este trabajo describe la metodología y resultados obtenidos para el diseño inicial de un sistema de bombeo y tratamiento de agua alimentado por energía solar fotovoltaica, que logra cubrir los 10 m^3 de consumo diario estimado de agua potable de la comunidad. Este diseño se realiza como parte del desarrollo de una Acción de Buena Voluntad en Campo Loro, con la posibilidad de transformarse en un Proyecto de Comunidad Sostenible. El sistema obtenido se compone de 52 paneles solares, una unidad de desalinización de electrodiálisis reversible, una unidad de desinfección electroquímica, una bomba sumergible para el agua subterránea y tres tanques de agua de 65 m^3, 10 m^3 y 10 m^3.

Purpose

The purpose of this work is to introduce the development of a Goodwill Action in the Ayoreo community of Campo Loro, Paraguay, and the process of designing an optimized solar PV water pumping, desalination and disinfection system for drinking and irrigation purposes. This work is done in the context of technological cooperation for sustainable development and resilience-building, and as one of the first steps towards developing a Sustainable Community Project in Campo Loro.

1. Introduction

The eradication of poverty has been of international concern for decades. However, despite the efforts and the progress that has been achieved so far, at present many areas still need very urgent attention, while others are worsening by the second. Poverty, hunger, and disease continue to be especially present in the poorest and most vulnerable regions, and the gradual rise of inequality within and between countries has meant that the lack of basic resources and services has become more widespread. Simultaneously, the rapid deterioration of our natural environment has significantly impacted communities living in poverty, majorly composed by rural population. This situation has derived into an increase in the amount of migrations due to climate related disasters, which in 2018 amounted to 17.2 million displaced people [1].

We are also at a time when the UN Sustainable Development Goals are at full fledge and their reach and efforts seem unlimited, but their mantra of "leaving no one behind" is not always being ensured by national transition plans. Smaller, local approaches to the problems permeating our world could be the preferred path of interest in this situation.

Under this light, the Sustainable Communities Project is being developed by the UN Committee of Local & Regional Leaders Appointment. With the goal of developing different routes of development and growth for small and often marginalized communities, the Project is oriented towards achieving sustainable development through the creation of resilience, the stimulation of reproducibility and the eradication of multidimensional poverty.

The work developed in this master's thesis corresponds to the first stages of development of a Goodwill Action in the Ayoreo village of Campo Loro, in the Paraguayan Gran Chaco, with hopes of this experience evolving into the development of a Sustainable Community Project. To understand the background of the Sustainable Communities Project, chapter 2 will focus on giving context on the definitions of Multidimensional Poverty and the Sustainable Development Goals, as well as Sustainability Transitions and the part played by the Sustainable Communities Project. Then, in chapter 3, an explanation of the reality of the Ayoreo people as well as a portrayal of the current situation in Campo Loro are given. Chapter 4 is dedicated entirely to the design of a water pumping and treatment system for the Goodwill Action, ending with the obtained results. These are meant to be interpreted as a first approach to the design of this system, as throughout its development no contact with the target community has been established due to the COVID-19 pandemic. Chapter 5 thus describes the steps that will follow this design. Lastly, the master's thesis is closed with the obtained conclusions.

2. Sustainable development

2.1. Multidimensional poverty

From the utilitarian-based approaches of the 19th century to the capabilities theory of Sen, poverty and welfare definitions, as well as their relevance and connection to development, have long been discussed and have evolved over the years [2], [3]. Since the late 20th century, it has been established that poverty is not necessary to development, and instead eliminating it should be the main goal of development [2]. Furthermore, as years passed, monetary-exclusive definitions of poverty lost the relevance and exclusiveness they had in the past. At present, countries and institutions have embraced the concept of multidimensional poverty, which considers the different types of deprivations people face in their daily lives [4].

Multidimensional poverty is built on criticism aimed at monetary-exclusive definitions: "poverty and social exclusion are interlinked with inequality but cannot be reduced to inequalities of income alone" [3]. That is, someone may earn more than the established limit for poverty, but still feel poor if lacking access to basic needs such as education, health care, or safe drinking water. In a direr situation, someone is unquestionably poorer when earning less than the established minimum *and* living without access to clean water or a safe environment [5].

The multidimensional poverty perspective has gained importance especially in the last decade, as the 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs) transparently consider poverty to be multidimensional [6]. In fact, one of the indicators used to measure progress against SDG1 is the Global Multidimensional Poverty Index (MPI), developed by the Oxford Poverty & Human Development Initiative together with the United Nations Development Program. It compares and monitors acute multidimensional poverty for more than 100 developing countries over time, by assessing three dimensions (health, education and standard of living) and 10 indicators, which are shown in Figure 1 together with their weight for the index. A community is defined as poor if it is deprived in indicators whose weight adds up to one-third or more of the total [7].

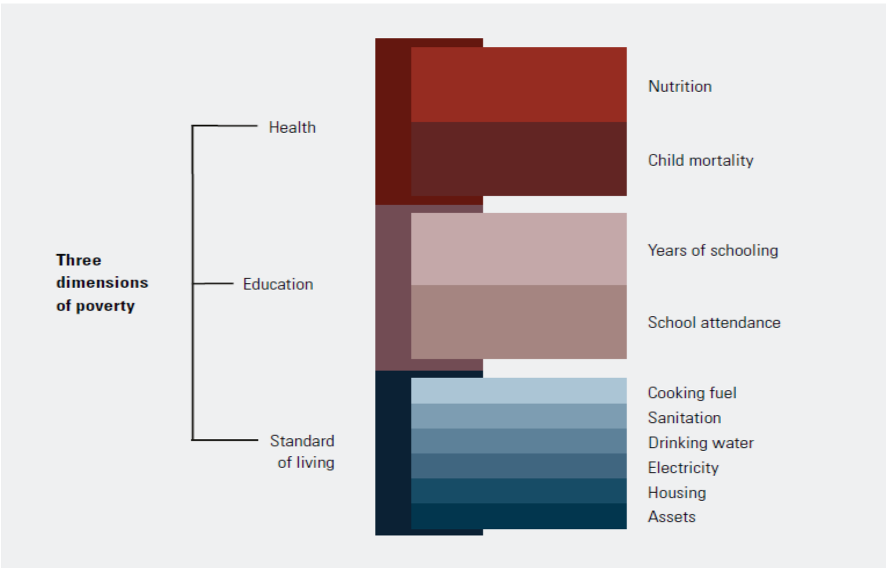


Figure 1. Structure of the Global Multidimensional Poverty Index [4].

As of 2019, 1.3 billion people across 101 countries have been found to live in multidimensional poverty [4]. This statistic is unsettling because of its quantity, but also because of its present context, where the looming menace of climate change and its effects are very likely to intensify poverty and increase risks in every aspect of human life. Therefore, if ending poverty in its multiple dimensions was one of the world's priorities because it implied better well-being and justice for all, it is also now essential because it often represents a highly effective form of climate adaptation [8].

To achieve poverty eradication the efforts need to be transversal and extensive. By considering poverty to be affected by many different factors, multidimensional poverty emphasizes aspects of human life that had not been considered when poverty exclusively meant having a very low or no income. It underscores that to lift all people out of multidimensional poverty one must profoundly work on several issues, such as health, education, access to water or to decent jobs. Such issues and the eradication of multidimensional poverty are at the core of the present work towards sustainable development embodied by the Sustainable Development Goals.

2.2. Sustainable Development Goals

In June 1992, the United Nations Conference on Environment and Development held in Rio de Janeiro culminated with the creation of Agenda 21: a comprehensive plan of action adopted by 178 countries towards achieving sustainable development in the 21st century. It is officially the first global agenda for Environment and Development to have ever been established [9], and it provided guidelines for governments to tackle pressing problems on sustainable development, reflecting a desire for global consensus and political commitment on development and environment cooperation.

Almost a decade later, during the Millennium Summit held in New York in the year 2000, the United Nations Millennium Declaration was adopted by 189 member countries, committing their nations to a new global partnership to address crucial issues such as peace, development, poverty reduction and sustainability [10]. Following its adoption, the partnership framework was outlined by the publication of the Millennium Development Goals (MDGs). Consisting of eight international development goals (Figure 2), each with their own targets and indicators, the goals aimed to achieve the rights set forth in the Declaration by 2015. Although this timeframe proved to be too ambitious, the final MDGs Report proclaimed that the efforts were not unfruitful: the 15-year endeavor had produced the most successful anti-poverty movement in history, its main achievement being the decline of people living in poverty by more than half, falling from 1.9 billion in 1990 to 836 million in 2015 [11]. Supporters of the MDGs also state that they were a powerful, common agenda of broad priorities that prompted governments to action and provided policy guidance towards defined human development objectives during its timeframe [12].

Figure 2. The 8 Millennium Development Goals [13].

However, progress across all MDGs was limited and uneven across countries. In the cases where targets were achieved critics suggest that it was in reality due to the rapid economic growth of China and India during the MDGs' timeframe, and not because of MDG-oriented activities [14]. On the other hand, the very results obtained by the MDGs were also doubted and questioned, due to calculations being made with data that was often poor quality (some targets relied on statistical tools that many countries lacked) and not necessarily comparable across countries (due to different compilation methodologies or definitions) [14]. Further criticism was aimed at the lack of attention to the synergies and interconnections between goals and targets, inadequate or absent incorporation of other important issues (such as environmental sustainability and inequality) [12], as well as not sufficient post-evaluation of the results of the performed actions.

As the MDGs' timeline approached its end, a new global development framework needed to be elaborated to continue with the efforts begun with these eight goals, but with the hope of improving and drawing lessons from their achievements and failures. In June 2012, at the United Nations Conference on Sustainable Development (Rio+20) in Rio de Janeiro, the Member states adopted the outcome document "The Future We Want", a declaration that reaffirmed the countries' commitment towards sustainable development and in which they decided to launch a process to develop a new set of goals, based on Agenda 21, and building on the results of the MDGs [9, 15]. In this process, global civil society and all 193 UN Member states were involved, to avoid the "donor-recipient" and "developed vs developing" relationship that the MDGs were accused of inducing [12].

Thus, in September 2015, the process culminated with the adoption of the 2030 Agenda for Sustainable Development by all 193 Members of the UN General Assembly, defined as "a plan of action for people, planet and prosperity" [16]. The 17 SDGs and 169 targets announced in the Agenda were envisioned as "comprehensive, far-reaching and people centered" [16], putting specific emphasis on "leaving no one behind", and recognizing that "ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests" [9]. Hence, the Agenda and its SDGs were envisioned to have a wider reach and to be more transversal and integrative than the MDGs, in an attempt to tackle some of their main perceived weaknesses. Key improvements were the emphasis given to pressing environmental issues, to promoting substantive equality between and within countries, to the transversality and interdependence between goals, and to sub-national disparities and regional specificities [12], [16]. The SDGs have also put diligent effort into developing a new set of reliable indicators to monitor progress across the SGDs, and into stressing the importance of gathering high-quality data [12].

Figure 3. The 17 Sustainable Development Goals [17].

A considerable amount of expectations has been placed on the achievement of these goals, partly justified because of the vast and increasing number of resources, work, monitorization and general interest taken in them. Yet, their success towards sustainable development and poverty eradication has been moderate, as can be derived from some of the key conclusions of the latest data (at the time of writing) on SDGs' progress, published in the SDG Report 2019 [18] in July 2019:

- The pace in eliminating extreme poverty has slowed and the world is not on track to achieving the established target. Projections suggest a remaining 6% in 2030.
- The number of people suffering from hunger has been increasing: an estimated 821 million people were undernourished in 2017, compared to 784 million in 2015.
- The proportion of people that have access to safely managed drinking water has increased from 61% to 71% between 2000 and 2017. However, 785 million people still lacked access to basic drinking water services in 2017, and this situation could worsen due to the intensification of water stress and scarcity heightened by climate change. By 2030, 700 million people could be displaced by intense water scarcity.
- In 2017, 89% of the global population had access to electricity, but 87% of the people lacking electrification lived in rural areas.
- Deforestation is slowing but continues at an alarming rate. An estimated 20% of the Earth's land area was degraded between 2000 and 2015.

Apart from these lukewarm results, another concerning aspect of the data given in the SDG Report 2019 is the vast difference in progress between regions. The SDGs are non-binding and respect each country's national policies and priorities, allowing them to create their own national or regional sustainable development plans. This aspect, paired with the substantial economic and development gap between countries, likely explains the difference between regional results, illustrated by the chart below.

Goal 1.1: Eradicate extreme poverty for all people everywhere								
World	Sub-Saharan Africa	Northern Africa and Western Asia	Central and Southern Asia	Eastern and South-Eastern Asia	Latin America and the Caribbean	Australia and New Zealand	Oceania	Europe and Northern America
Moderate poverty	Very high poverty	Low poverty	Moderate poverty	Low poverty	Low poverty	Low poverty		Low poverty
The progress chart operates on two levels. The text in each box indicates the present level of development in the specific area addressed by the indicator and based on the latest available data. The colors show progress made toward the targets according to the legend below:								
Target met or likely to be met by 2030/substantial progress						Moving away from the target/deterioration		
Fair progress but acceleration is needed						Insufficient data/not applicable		
Limited or no progress								

Figure 4. SDG 1.1 progress chart at global and regional levels. Trend assessment based on progress from 2010 to 2015. (Chart adapted from [19]).

The disparity is not limited to the regional level: it is also clear between rural, peri-urban, and urban areas. As of 2019, conditions for individuals living in rural areas (who mostly live in developing countries) are worse than their urban counterparts by almost any development indicator, with around 80% of the world's poor living in rural areas, an extreme poverty rate three times higher and a lack of access to electricity, clean drinking water and sanitation, among other services [18], [20]. On the other hand, the world is becoming increasingly urbanized, projecting an estimated 60% of people living in cities by 2030 [18]. These urban areas are often supported by surrounding peri-urban and rural areas which show high rates of poverty [21]. However, poor rural individuals who migrate to cities with hopes of improving their quality of life are more likely to join the large numbers of urban poor. Escaping poverty is more probable for these individuals if they remain in rural areas [22].

A specific situation that could be included in the rural population problematic is that of the indigenous people. They can be defined as minorities (compared to the dominant culture of their country) who usually have or had their own distinctive cultural traditions and language, as well as a traditional territory with which they maintain a strong connection [23]. There are an estimated 370 million indigenous people in the world, primarily living in rural areas of developing countries, and they currently sustainably manage at least 50% of the world's lands. However, they only have legal ownership rights to 10% of those lands, and despite representing 5% of the world's population, they constituted 15% of the world poor and 33% of the world's extremely poor in 2019 [24]. Although two of the SDGs indicators directly refer to indigenous people (Indicators 2.3.2 and 4.5.1), and with most of the SDGs being applicable and relevant to these communities, actions towards improving their wellbeing and rights in national plans are still scarce and without sufficient budget allocation. In fact, economic growth targets in the territories of indigenous peoples continue to be extractive in nature, and protection of their rights to their lands and resources and their effective participation in decision making are often forgotten.

As observed, current results from the SDGs are disheartening. Perhaps more reflection is needed on the concept of sustainable development and the transitions executed to achieve it. Attaining an adequate and efficient transition towards a more just and sustainable society has proven to be complicated: with such vast issues and inequalities occurring in their target territories, global, national and regional sustainable development plans struggle to correctly assess and address these issues. Different approaches that enable governments to correctly design SDG-based transitions are necessary, in an effort to lower the unpredictability and risk that accompany systemic change. This mixture of approaches must enlighten us about the structure, drivers, and dynamics of production-consumption systems at different scales. Implementing alternative structures that provide evidence that enables society to learn from successes and failures is also fundamental.

A project that serves such functions is presented in the following chapter.

2.3. Sustainable Communities Project

Created by the UNESCO Committee of Local & Regional Leaders Appointment (CLRLA) in 2012, the Sustainable Communities Project (SCP) is an initiative whose goal is the creation of a comprehensive and holistic local development model focused on small communities [25]. The approach is chiefly based on the implementation of appropriate technologies and sustainable solutions, coupled with renewable energies, to fulfill a community's needs with minimum external dependence.

Originally, the Project was established to validate how the Low External Dependence Distributed (LEDD) model utilization could directly achieve poverty reduction in these communities. The LEDD model is chiefly based on the concept of community resilience, which looks at the ability a social and institutional system has to confront adversities and reorganize itself, improving its structure, operation, and identity [26]. However, the goal of SCP has nowadays broadened to validating sustainability transitions approaches premised on increasing resilience, the utilization of local resources, and multidimensional poverty eradication.

The Project's initial working hypothesis considers that any given community, no matter their cultural, social, economic, or geographical background, is able to fulfill their needs and expectations while being socially, economically, and ecologically sustainable. To achieve this, the two pillars of SCP design and implementation are: a horizontal cooperation structure, where the priorities defined by all concerned or participant actors are considered until a consensus is achieved, and respect towards the community, their culture and lifestyle [27].

2.3.1. Methodology

Approximately 5 years are needed for the complete implementation of a Sustainable Community. The development of the project is divided in 5 phases, each with its own specific execution period, as well as an intermediate evaluation stage, to ensure continuous control and monitoring of the project's interventions and actions [27].

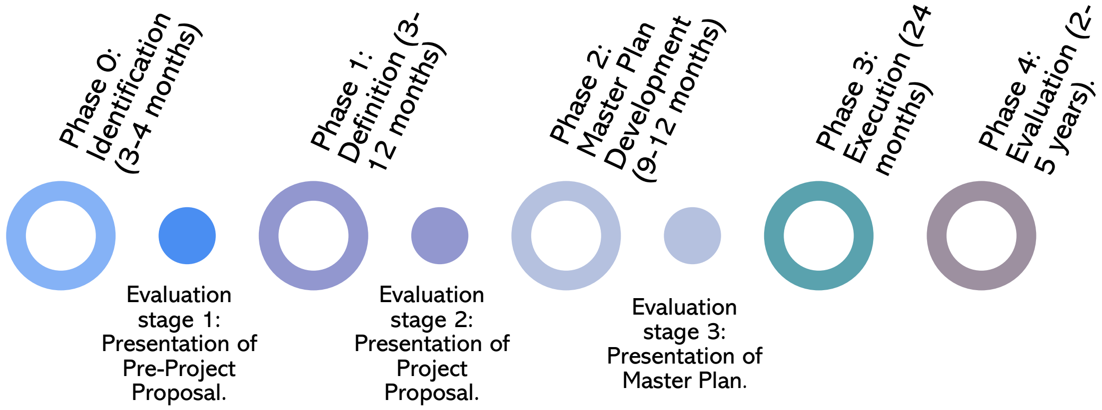


Figure 5. Phases within a Sustainable Community Project development and implementation.

Phases	Activities
0	Pre-project Proposals, either presented by institutions not involved with the target community (UP-DOWN) or by local entities involved or from the community (DOWN-UP), are evaluated by UNESCO CLRLA. A decision is taken by the Committee considering several criteria, such as community size (<20.000 inhabitants), connection to the electricity grid, location in target regions (see section **2.3.3**), multidimensional poverty indicators, etc. If the PPP is deemed suitable, a first SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) is requested. The PPP and the SWOT analysis are then evaluated by the Regional Coordinator, and the Pre-project is approved or discarded.
1	A first complete Project Proposal is elaborated, which should contain information on all involved members, sustainability criteria used throughout the project, reasons for implementation, organizational and operative project structure, evaluation methodology, estimative budget and a chronogram. The Project Proposal is presented to the Regional Coordinator, which elaborates a Project Supervisor Report. Then, both documents are sent to the CLRLA evaluation committee for approval.
2	This phase is dedicated to the development of a Master Plan, in which an integral diagnosis is performed of available resources, community sociocultural and economic context and their needs and expectations. Information is gathered on 7 different areas of action (see section **2.3.2**) and appropriate technologies are chosen. Once completed, the Master Plan is first presented to the community's members or representatives. If endorsed, then it is presented to the CLRLA Committee by the Regional Coordinator. Recommendations may be given before final approval.
3	Actions detailed in the Master Plan are fully or partially implemented, depending on available time, funds, and priorities. Two main logistical groups of action are considered: Technical actions, which include implementation of new technologies or improvements on existing ones, and Formative actions, designed to train and teach the community knowledge in various fields, often related to the performed technical actions.
4	A final evaluation (as well as periodic ones afterwards) is performed on the sustainability of the project and its impact on the community's development. It is based on indicators which depict the performance and the community's acceptance and adoption of the implemented actions, as well as progress in SDGs. The evaluation, monitoring and control of these indicators is continuous, to identify both short and long-term problems in the project's execution.

2.3.2. Areas of action

During phase 2 an integral evaluation of the community is performed. A fair picture of the context of the community is thus assembled for the development of the Master Plan. Then, various scenarios of action are sketched out, containing different addressed issues and appropriate solutions separated in areas of action.

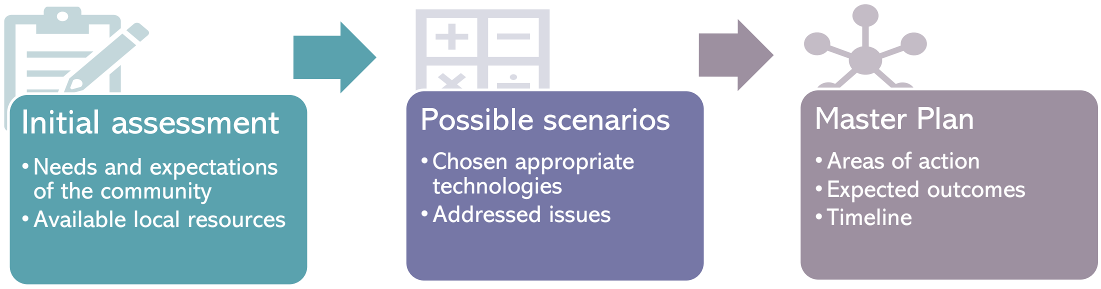


Figure 6. Diagram of the development of the Master Plan in Phase 3.

Under each considered area of action, which are normally the 7 groups defined in Figure 7, available resources and context of the community are evaluated. In Infrastructures, for example, the availability of local traditional materials, knowledge on bioclimatic and ancestral construction methods, and infrastructural needs of the population are considered.

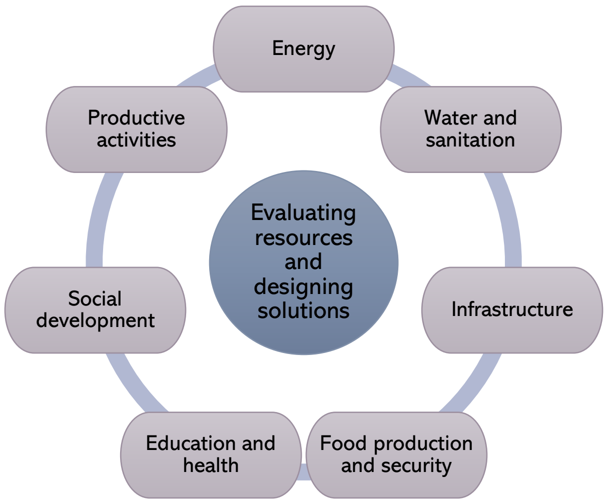
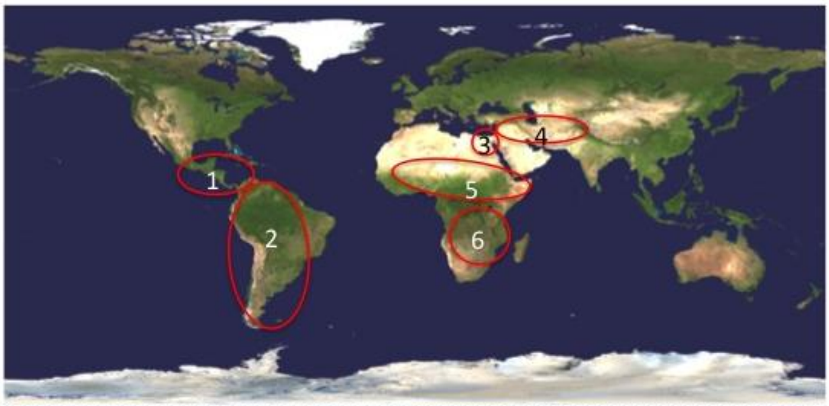


Figure 7. Areas of action.

Once the current situation of the community and its background are correctly and integrally defined, appropriate solutions are studied and discussed with the community. As can be predicted, information gathered for one area of action can be important for others when examining solutions, as interlinkages are evident: the social development of the community can be achieved through changes and empowerment strategies in education or energy management; ensuring food security is intimately linked with having a continuous and abundant water supply; a healthy community is only achieved with safe water for drinking and cooking, sufficient food for the inhabitants, energy to cook and to withstand cold periods as well as an adequate home for shelter; etc. A transversality is established throughout the Master Plan, very much like the MPI and SDGs, where all dimensions must be taken into account so as to ensure that minimum trade-offs happen, that resilience is being built, and that multidimensional poverty is being eradicated in all areas.

2.3.3. Target regions

At present, the Project's goal is to achieve implementation in two hundred communities by 2030 in the six selected territories shown in the Figure below. Most of the chosen communities are rural, and their regions are some of the most affected by poverty or war conflicts and less benefited from advances during the MDGs [27]. They also show an increased amount of climate migrations. Therefore, the Sustainable Communities Project can also be regarded as an effort to lessen the differences in SDGs progress between regions and between rural and urban communities.



1. **Central América and Caribbean (Nicaragua, Guatemala, Honduras, Cuba, El Salvador, Panamá)**
2. **South América (Argentina, Chile, Perú, Colombia, Bolivia, Paraguay, Brasil)**
3. **Palestina**
4. **Central Asia (Kazakhstan,Kyrgyzstan,Tajikistan,Uzbekistan, Armenia)**
5. **Horn of Africa (Mali, Chad, Sudan, Ethiopia, Somalia, Eritrea, Yibuti)**
6. **Austral Africa (Angola, Malawi, Mozambique, Zimbabwe)**

Figure 8. Six selected regions for the implementation of 200 SCP between 2014 and 2020 [27].

Interest has been placed in developing a Sustainable Community Project in the Ayoreo village of Campo Loro. It is a rural indigenous community located in Paraguay, which is included in the target regions marked in Figure 8, and in a current situation of multidimensional poverty that will be explained in the next chapter.

3. The Ayoreo

3.1. Deforestation of the Paraguayan Chaco

The Gran Chaco is a hot and semiarid lowland natural region, whose territory lies in four different South American countries: Paraguay, Argentina, Bolivia, and a very small part of Brazil. It has historically been divided in three parts: the Chaco Austral, south of the Bermejo river; the Chaco Central, between the Bermejo and the Pilcomayo rivers; and lastly, the Chaco Boreal, comprising the territory from north of the Pilcomayo up to the Brazilian Pantanal. This last subregion, the Chaco Boreal, may also be divided in two territories because of their different climatic characteristics: the Chaco Seco (Dry Chaco), drier and sparsely vegetated, and the Chaco Húmedo (Humid Chaco), with less arid conditions and higher rainfalls [28].

The Gran Chaco can also be divided by political borders, with four subregions: the Paraguayan Chaco, the Argentinian Chaco, the Bolivian Chaco, and the Brazilian Chaco.

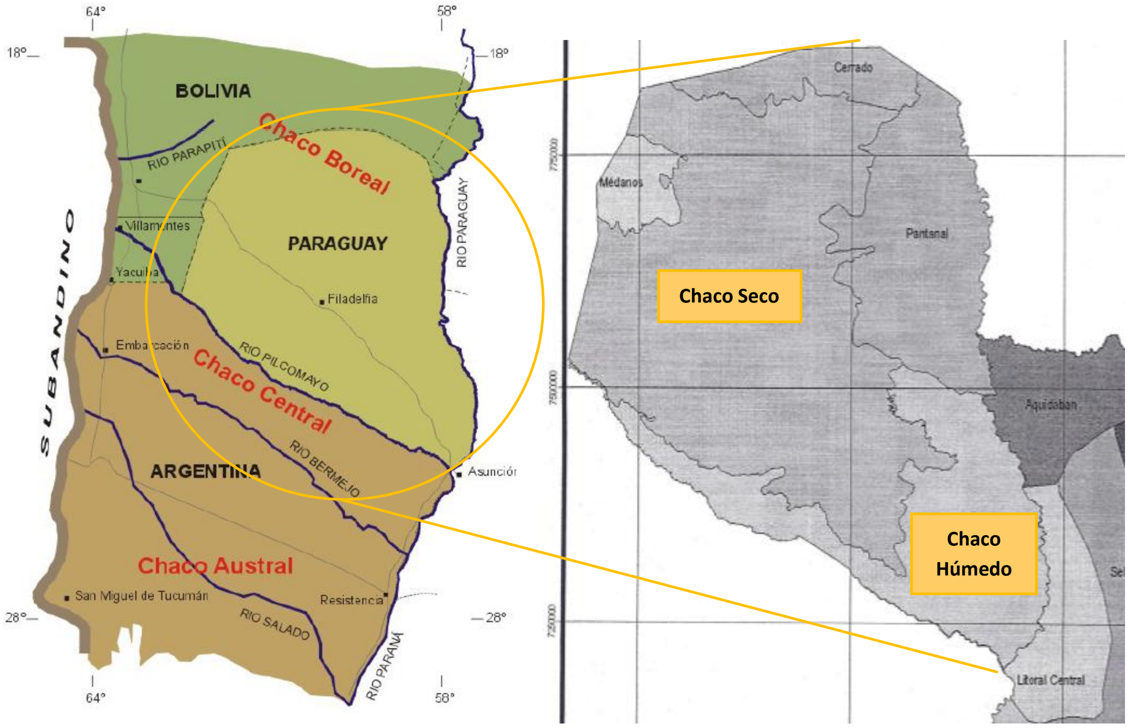


Figure 9. Map of the Gran Chaco, with its three historical subregions [29] (left) and Paraguayan ecoregions of the Gran Chaco [30] (right).

The Paraguayan Chaco, which comprises parts of both the Dry Chaco and the Humid Chaco, is a territory characterized by its high biodiversity, with several species of fauna and flora and important surfaces of virgin forests spread through its land. Historically, the Paraguayan Chaco was sparsely inhabited by indigenous people, with colonization beginning late and the first settlements only being established in the 1920s by Mennonite immigrants [31]. It has long been considered an underdeveloped region because of its lack of basic infrastructure, which made agricultural expansion in the Paraguayan Chaco difficult. However, with increasing importance of cattle for the country's export, cattle ranches spread through the Paraguayan Chaco in the last few decades of the 20th century, deforesting a calculated total of approximately 14.000 km^2 between 1987 and 2000 for this purpose [31].

Nowadays, the situation has become direr: deforestation more than doubled in the Paraguayan Chaco between 2001 and 2012 (approximately 29.000 km^2) compared to the 1987-2000 period [31]. This is mainly due to the suitability of the land to grow fuel crops, the increasing importance of Paraguay's soy and meat exportation (of which Paraguay is the 4th and 8th biggest exporter in the world, respectively) [32], loose regulations, and the enactment of the Land Conversion Moratorium for the Atlantic Forest of Paraguay in 2004, prohibiting the transformation and conversion of forested areas in the eastern region of Paraguay (which had been one of the most endangered tropical forests at the time due to deforestation) [33]. Recent data gathered by the Paraguayan Ministry of the Environment and Sustainable Development concludes that approximately 1 million ha have been deforested between 2014 and 2018 in the Paraguayan Chaco [34], with more than 90% of the deforestation happening in the provinces of Alto Paraguay and Boquerón. In total, around 5.3 million ha have been deforested in the Paraguayan Gran Chaco in the last 3 decades.

This massive deforestation driven by the agriculture and cattle sectors has positively impacted Paraguay's economy, exhibiting some of South America's strongest economic growth in recent years [35], [36]. Still, one could argue that the negative consequences far outweigh the positive ones: apart from usually being done illegally, Paraguayan Chaco's deforestation and agricultural boom result in biodiversity loss and intentional killing of species (like jaguars) that are a menace to cattle [35]; it contributes to land degradation, a problem exacerbated by climate change because of increased heavy precipitation and heat stress, and it is also a driver of climate change, through the emission of greenhouse gases and reduced carbon uptake by deforested land [37]. Furthermore, the deforestation is driven by individual interests of agricultural companies, often from foreign countries like Brazil and Uruguay or owned by wealthy Mennonites from the Dry Chaco, with minimal concern towards environmental conservation and its impact on Chaco's indigenous communities [4], [8], [9]. Indigenous communities are disproportionately affected by deforestation due to a lack of access to secure land tenure and general multidimensional poverty [9]. Land-use changes for agricultural purposes also mean many indigenous people have been displaced from their homes by new landowners or have been denied entrance to areas they depended on for subsistence agriculture or resources gathering [35], [38]. In addition, the wildlife reserve Defensores del Chaco National Park, which is the home of a group of Ayoreo in voluntary isolation, is being threatened by deforestation as well [34], [36].

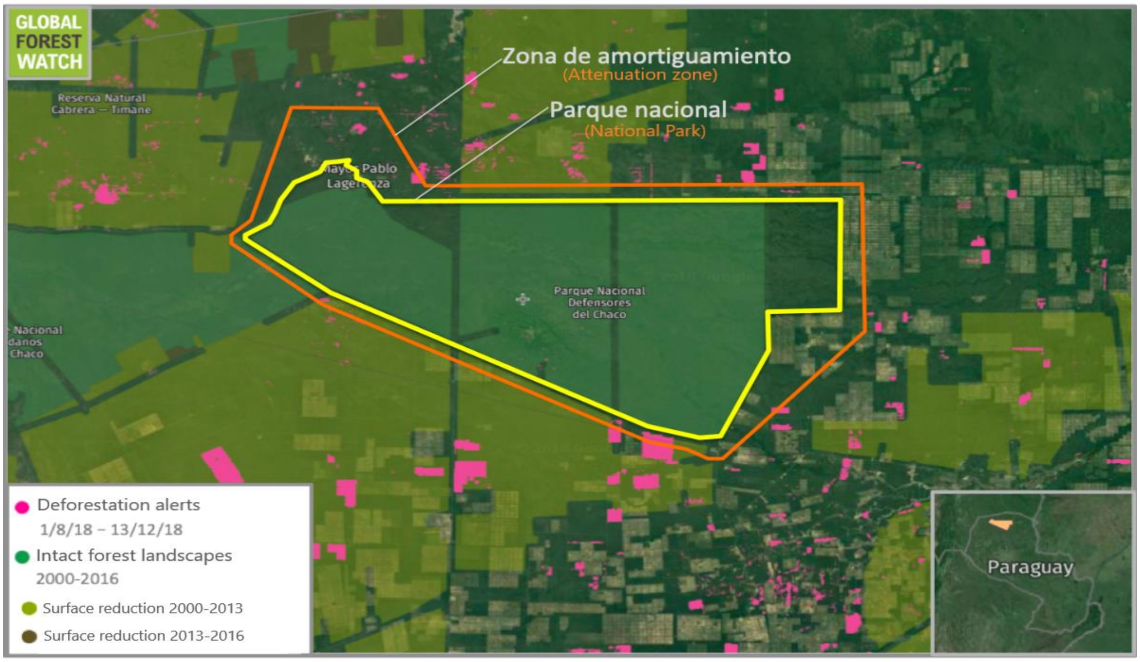


Figure 10. Recent deforestation around the Defensores del Chaco National Park and in its attenuation zone. (Image taken from [34], created with information from Global Forest Watch [39]. The image has been edited to translate it into English).

Some measures to combat this menace have been deployed, like the removal by current President Mario Abdo Benítez of a 2017 decree that enabled unlimited deforestation in the Chaco, or the effort made by associations and initiatives for the development of sustainable agriculture and forest conservation in this region [34]-[36]. Nonetheless, at present the deforestation of the Paraguayan Chaco has not stopped.

3.2. Current situation of the Paraguayan Ayoreo

The Ayoreo are an indigenous people from Chaco Boreal, whose territory until mid-20th century covered more than 30 million ha spread between the Paraguay, Pilcomayo, Parapetí, and Río Grande rivers (thus spanning both Bolivia and Paraguay). Traditionally nomadic people, they moved in flexible, autonomous groups whose subsistence depended on hunting and gathering. Their culture and lifestyle are traditionally deeply connected to their land (called *Eami* in the Ayoreo language) and the resources it offers, moving when they are scarce due to their presence and leaving their temporary settlements to let nature regenerate during their absence [40]-[42]. As of 2013, around 3,000 Ayoreo lived in Bolivia, and 2,600 in Paraguay [41].

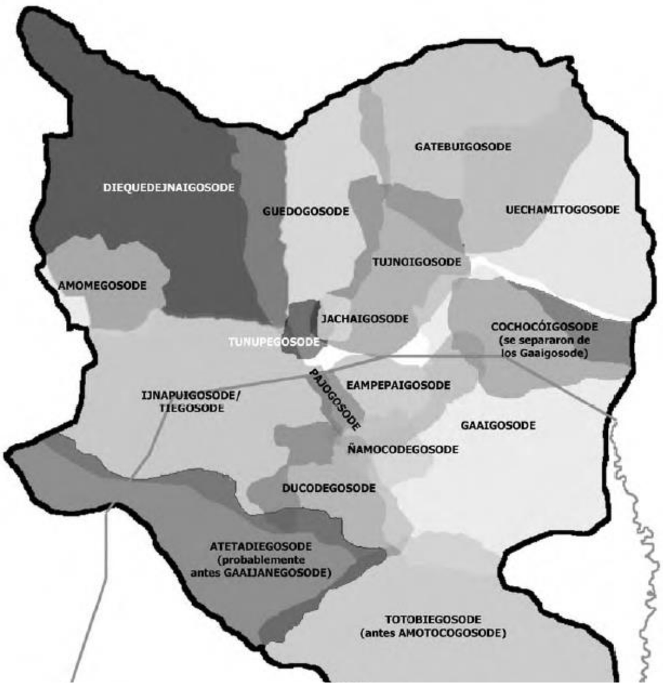


Figure 11. Map of traditional Ayoreo territory, with each group's own territory colored in different shades of grey. The grey line indicates the Paraguayan border [41].

The very first contact with the Ayoreo was made by Jesuits inside Paraguayan borders in the mid-18th century, who tried to convert the Ayoreo to Catholicism. However, Paraguayan Ayoreo were still able to maintain their lifestyle and culture, living freely in their territory away from occidental society up until the late 1960s. It was then that Christian missionaries in Paraguay, particularly Mennonites, made forced contact with many Ayoreo groups and used violence and manipulation to remove the Ayoreo from their native territory and into their mission stations, located near Mennonite and Salesian colonies (such as Filadelfia and Colonia Carmelo Peralta, respectively). Many Ayoreo did not survive the forced migration. The survivors, on the other hand, had to adopt a sedentary lifestyle, occidental culture, a new diet, and Christian beliefs [41].

With the Ayoreo away from their land, in the decades after their forced contact, third parties claimed portions of the land, usurping Ayoreo territory. The deforestation process described in section **3.1** started at this moment and worsened as companies expanded and began to apply intensive farming and ranching methods.

Deforestation poses an immense threat to the Ayoreo: it destroys an irreplaceable part of their culture; it forces the Ayoreo to move closer to cities and slums, further away from their native territory; it contributes to land degradation, which increases the chances of wildfires (the Paraguayan Gran Chaco was affected by frightening wildfires in September of 2019 [43], [44]) that most times reach indigenous communities and become life-threatening; and lastly, it poses a terrible menace to the few groups of Ayoreo living in voluntary isolation in different parts of the Paraguayan Chaco. Reasonably, the Ayoreo are at present some of the most important activists against this deforestation. They collaborate with the government and NGO's to monitor and spread awareness on how it threatens their human and indigenous rights [35], [36], and to reclaim their rights to their ancestral land.

In summary, the Ayoreo suffer from an accelerated pauperization and loss of autonomy. They often must accept jobs with precarious work conditions, notably in cattle ranches and farms. They are dependent on many factors on a society foreign to theirs but are simultaneously object of discrimination. In these conditions, the Ayoreo have little opportunity to escape multidimensional poverty and achieve an acceptable standard of life [40], [41].

3.3. Campo Loro

The Ayoreo village of Campo Loro is a community of roughly 900 people, located in Chaco Seco in the Boquerón Department (coordinates: 22°04 S, 59°51 W). 50 km away from Filadelfia, Campo Loro is the most populated Ayoreo village in Paraguay. According to the Paraguayan Indigenous Communities Atlas ("Atlas de las Comunidades Indígenas en el Paraguay") [45], apart from the inhabitants' homes, it also has a community center, a healthcare center, a playfield, a school, a church, and a pottery.

Figure 12. Satellite view of Campo Loro. Taken with Google Maps, 2020.

Campo Loro has been suffering from water scarcity for some time. Precipitations in its area are generally low, with a wet period expanding between October and April with a maximum average rainfall accumulation of about 110 mm per day, and a drier period whose minimum value is reached usually in July, with 10 mm of rainfall per day [29], [46]. The population, not being able to subsist on collected rainfall, used to depend on the village's well, but the water now extracted from it is not suitable for human consumption due to its high salinity. They have since had to depend on the Filadelfia Municipality, the Boquerón government, or nearby Mennonites for their water supply, which is brought irregularly and insufficiently in water tank trucks [47]. Apart from water shortage for human consumption, there is also no water for crop irrigation, which leaves Campo Loro in the extremely precarious situation of water scarcity and lack of food security. Additionally, an important part of the population is not employed or works in a precarious or informal job, thus completing the picture of a village facing multidimensional poverty and far from achieving various SDGs (namely SDG 1, SDG 2, SDG 6 and SDG 8).

Figure 13. Inhabitants of Campo Loro leaving the village to search for water in other communities in April 2020. The water shortage has been aggravated with the arrival of the drier season coinciding with the COVID-19 outbreak. Image credits: Iniciativa Amotocodie [48].

Recent events such as the COVID-19 outbreak and the news that Campo Loro would finally not benefit from a pipeline being constructed by the Paraguayan Ministry of Public Works and Communications in the Gran Chaco have put the community in the direst of situations. A system capable of providing a stable and safe water supply, such as the one designed in the next chapter, is a priority at the moment and essential for the wellbeing of the community.

4. Designing a solar PV water pumping and treatment system for drinking and irrigation purposes in Campo Loro as the first step in a Sustainable Community Project

4.1. Goodwill action

This master's thesis focuses on the development of a Goodwill Action, which can be defined as a small technological cooperation project developed collaboratively by a community and a group of experts. They are small projects oriented to solving key issues present in a community. However, in our case, it has special relevance, as a possibility has arisen to develop a Sustainable Community Project with the community of Campo Loro. Thus, the development of this Goodwill Action is also undertaken as a "first exposure" experience between the community and the group of experts, and will follow the premises and criterion established by the SCP of choosing appropriate technologies and horizontal cooperation.

The direction in which Goodwill Actions are directed is important: scenario making and defining are crucial, since communities will usually have various issues that need solving, but not all of them can be addressed immediately.

In our case, the first proposal for the Goodwill Action for Campo Loro was a solar-powered electrical and illumination system. This was the first considered scenario, as the information obtained at that point was that the electrification of the Paraguayan Gran Chaco was still in its early stages, with many areas still not connected to the Paraguayan national electrical grid. Thus, calculations were made to design a solar powered system that could illuminate and provide electricity for the 150 residential houses in Campo Loro and/or all of the community buildings, taking into account the consumptions of different electrical appliances such as fridges, phone charging stations and televisions, which were distributed between the public buildings for the whole community to use.

Table 1. Lighting and electricity-powered elements considered in the design of the solar-powered illumination and electrical system for Campo Loro.

Building	**Nº**	**Needs**						
		Lighting		**Electricity**				
		Per building	**Total**	**Fridge**	**TV**	**Computer**	**Battery charging station**	**Phone charging station**
Houses	190	6	1140					
School	1	8	8	1	1	3	1	
Church	1	8	8					
Health center	1	8	8	1		1		
Pottery	1	8	8					
Community center	1	8	8	1	1	1		1
Playfield	1	0						
Street			20					
TOTAL		-	1200	3	2	5	1	1

Table 2. Results obtained for the three different considered designs in the first proposal.

	Design 1: microgrid powering houses and public spaces.	**Design 2:** microgrid powering only public spaces.	**Design 1:** microgrid powering only 56 houses.
Solar panels (370 Wp, 24 V)	70	10	18
Batteries (250 Ah, 12 V)	40	10	20

After this system design was made, we contacted Iniciativa Amotocodie, which is a Paraguayan NGO that centers its work around protecting the Paraguayan Gran Chaco and the people that live in its territory, especially the Ayoreo. They mainly focus on accompanying the Ayoreo in their process of defending their land, their culture, and their way of life [49]. Our desire was to be able to gather more information and to reach out to people that could establish a connection between the development of the project and the Ayoreo people of Campo Loro. The proposal for a solar powered system for illumination and electricity for Campo Loro was presented to them, and they informed us that the community was partially electrified, with 50% of the houses having access to the electricity grid. Although this system could be improved to achieve a total electrification of the village, they described the situation of extreme water scarcity in Campo Loro.

The scenario of the Goodwill Action clearly changed after being presented with this new information. Water scarcity in a community affects many aspects of its well-being: by checking the areas considered in the MPI (described in section **2.1**) and in the Master Plan for the Sustainable Communities Project (see section **2.3**), we can observe that access to a stable supply of clean water improves the health of a community, provides food security (as it allows the community to plant and irrigate their own crops if fertile land is available) and improves sanitation and hygiene of its population. It is an urgent issue that must be tackled by the Goodwill Action, which therefore evolved into designing a system that could solve the water shortage of Campo Loro.

4.2. Initial considerations

To be able to design the needed system, the intent was to visit the community during the month of April. The main purpose would be to perform measurements to shine some light on the composition of Campo Loro's groundwater and its salinity content, as these are extremely important parameters to consider when choosing the adequate treatment processes to convert it to potable water. However, due to the worldwide spread of the COVID-19 virus and the subsequent imposed lockdowns in many countries, traveling to Campo Loro to obtain this information was proven impossible during the development of the design. Therefore, the necessary information had to be searched in available literature on the topic, which is not extensive, unfortunately. Relevant data was found in [29] and is shown in Figure 14.

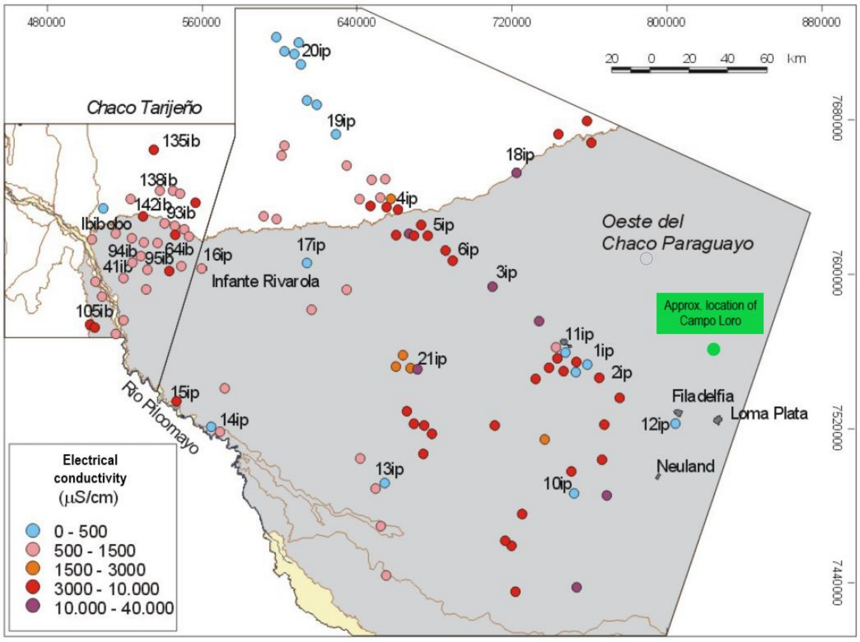


Figure 14. Groundwater electrical conductivity in the aquifers to the east of the Pilcomayo River [29].

The closest measured point to Campo Loro is that of Filadelfia, which shows an electrical conductivity in the range of 0 – 500 µS/cm. However, this cannot correspond to the salinity in Campo Loro, since the range found in Filadelfia means that its groundwater is suitable for drinking, while the testimony of Campo Loro's population is that its local groundwater is not. As the other closest points to Campo Loro mostly show a range of 3,000 – 10,000 µS/cm, this design considers Campo Loro's groundwater to have a salinity 6,000 µS/cm, which corresponds to a TDS (Total Dissolved Solids) of approximately 3,500 ppm (or mg/L).[1]

If this is the salinity considered for the local groundwater, the water system designed for Campo Loro must include a **desalination unit** to convert the brackish groundwater to drinking water and a **potabilization unit** to make it suitable for human consumption, as well as a **groundwater pump** and an **energy supply** to power all the elements. Other units or elements could be needed if the composition of the local groundwater included arsenic or other undesirable components. However, as no information is available on this matter, this design only considers desalination and potabilization as the two necessary treatments.

Thus, the stages for the development of the design are as follows:

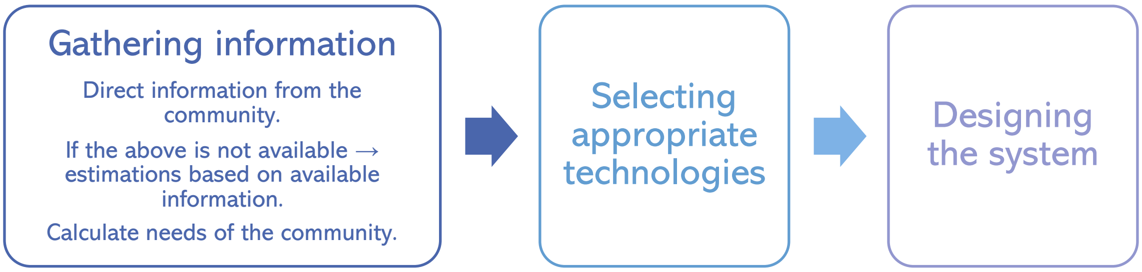


Figure 15. General stages to develop the design of the system.

Therefore, before proceeding to select the technologies used in the design, an assessment of Campo Loro's daily water consumption is needed. As directly asking the community for a detailed disaggregation of their water uses has been difficult, an estimation of Campo Loro's daily consumption is used for this system design.

The main necessities that should be met are Campo Loro's need of potable water for:

- drinking, cooking and hygiene,
- to water the crops planted in the village's fields,
- for their animals to drink.

According to [51], at least 2.5 L/day per person are needed to cover a person's drinking requirements, and this will be the value used in this design for drinking necessities. Then, 2.5 L/day per person are added to minimally cover basic hygiene practices and minimum cooking needs, and 5000 L/day for irrigating 5000 m^2 of agricultural land. No information is available on what kind or quantity of cattle Campo Loro has, and we also do not know if the cattle is theirs or owned by the Mennonites but cared by the Ayoreo of Campo Loro. Thus, a symbolic volume of 500 L is considered for cattle in this estimation.

In total, with the population of Campo Loro being 900 people, the system would need to supply at least 10 m^3 a day of suitable to drink, desalinated water for Campo Loro to fulfill its needs. It must be noted that, although higher quantities of water are advised for cooking and hygiene than what is considered in this work, we have decided to compromise in these categories as the top priorities of this design are to supply enough water for the population of Campo Loro to drink and for irrigation.

[1] Conversion of electrical conductivity to TDS is done using a 0.6 conversion factor, as seen in [50].

Table 3. Daily water consumption considered in this system design for Campo Loro.

Campo Loro	
Population	900
Main crops	Corn, watermelon, squash, kidney beans
Considered cultivated land	5,000 m²
Volume of water per person per day	2.5 L (drinking) + 2.5 L (cooking & hygiene)
Volume of water per m² of cultivated land	1 L/m²

Disaggregated daily water consumption	
Human consumption	4.5 m³
Crops (irrigation)	5 m³
Cattle	0.5 m³
TOTAL	**10 m³**

When more information is available, the estimation of cattle consumption as well as the rest of the water demand of Campo Loro will be reconsidered. Still, 10 m³ of desalinated water is adequate for covering the basic needs of a village the size of Campo Loro and, if the distribution of the demand proves to be different once the community is asked directly, the volume of desalinated water can still be kept at 10 m³ but be distributed differently for the desired purposes.

With the information gathered and the considered estimations of groundwater salinity and water demand of Campo Loro, we can proceed to choosing the most suitable technologies for the design of the system. Appropriate technologies need to be chosen for water treatment and pumping, as well as for energy generation or supply. This will be the focus of the next section, where each selected technology will be explained, as well as the reasoning for selection and the key expressions used during the design.

4.3. Selected technologies

4.3.1. Solar photovoltaic energy generation

The desalination and potabilization technologies chosen for this design (which will be explained in the following sections) as well as groundwater pumps need to be supplied with electricity. Many options are available to power these elements, such as connecting it directly to the grid or using a diesel generator. However, using a renewable energy for this purpose is more desirable since it is more sustainable and uses local resources.

The natural resource that is more likely to be of use in the Gran Chaco is solar irradiation, as water sources or wind intensity are not outstanding, and using biomass for power generation would have the two main inconveniences of increasing deforestation and competing with the use of biomass for heating and cooking in these communities. Thus, using solar power seems the most reasonable option.

Two types of radiation data have been obtained for this design to be able to assess the available solar resource in Campo Loro:

- Global horizontal irradiance (GHI) data in intervals of 30 minutes from 2010 to 2018 from the NSRDB-PSM model [52]. The model does not reach the area of Campo Loro, thus a location at (20.95°S, 60,74°W), 155 km away from Campo Loro was chosen.

- Experimental GHI data in intervals of 10 minutes acquired by the Meteorology Department from the National University of Asunción, from the 27th of September 2016 to 12th of May 2020, in the closest available meteorological station to Campo Loro. It is located in Filadelfia (22.36° S, 60.03° W), approximately 50 km away from the community. This data set was fairly incomplete, with around 45% of null values. Thus, the data acquired throughout the 3.5 years was used to create an average annual experimental GHI data set. The experimental GHI values were calculated to intervals of 30 minutes instead of 10 to make it easier to compare to the model data.

The monthly average daily radiation of the two data sets is shown in Figure 16.

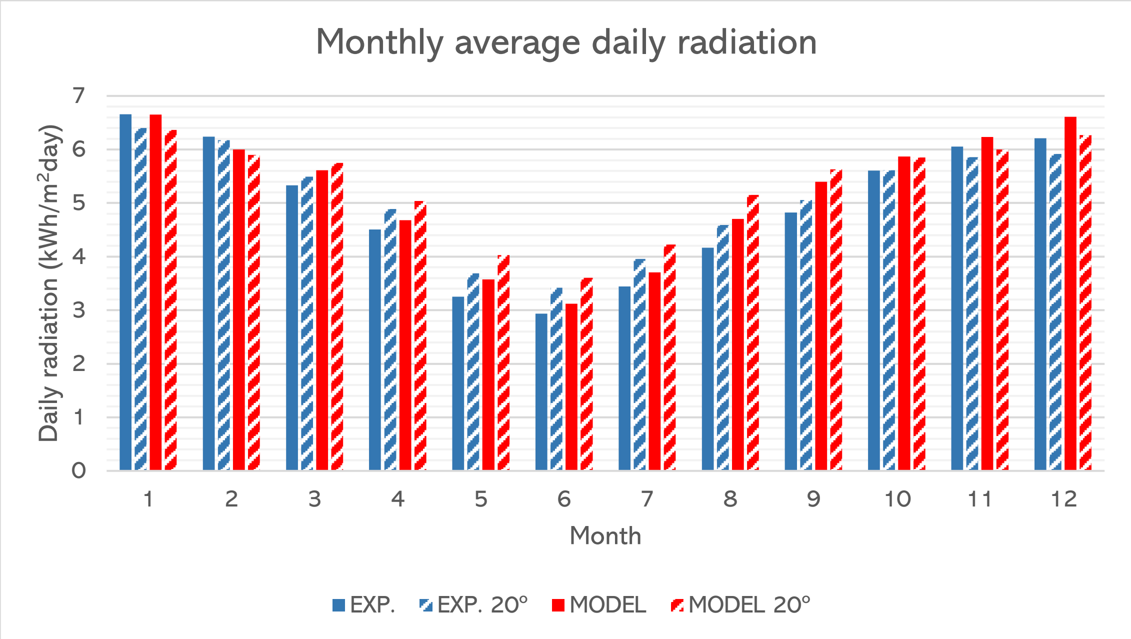


Figure 16. Monthly average daily radiation from the experimental and model radiation data sets on a horizontal 20° angle surface.

Both the experimental and model data show very high irradiance values throughout the year, which justifies choosing solar power to supply the system. Since the system will need electricity to operate, the selected technology is hence solar PV. This technology requires little maintenance and easily allows further expansion of the system if necessary, which gives the opportunity of satisfying other needs of the community with this system in the future.

The radiation values on both data sets were calculated for a surface of 20°, as equaling the tilt angle of your panel to the latitude of the location where they are being installed is often recommended when on a fixed mount, and this is what will be done in our system. See method of calculating irradiation on a tilted surface in **Annex A**.

4.3.1.1. Description and context

Photovoltaic (PV) solar energy is one of the most globally deployed renewable energies, and its decreasing costs and rising efficiency make it one of the most promising renewable technologies in the next decades. Because of its modular nature, its applications range from small-scale, off-grid applications to large, utility-scale implementations [53]. Being a renewable energy, its deployment is key to achieving SDG 7, but it can also contribute to progress in other goals as well: decentralized renewable energy deployment in poor communities can drastically reduce the costs incurred from generating electricity with polluting diesel generators, therefore assisting in poverty reduction (SDG 1), and by pairing these renewable energy technologies with water extraction and treatment systems and/or with refrigerators, food security, nutrition, and access to clean water can be improved and secured in these communities (SDG 2 and 6) [54].

In PV solar energy, electricity is generated through the photovoltaic effect using solar cells. One solar cell does not generate enough energy to power almost any load, so they are put together in modules and electrically associated. Then, one or more modules are wired and framed together to form a solar panel. Panel lifetime is usually estimated at 20-25 years, and different kinds are available commercially. General classification of panels is usually done based on solar cell configuration and semiconductor materials. Although various kinds exist, only three of them are commercially widely deployed: Monocrystalline silicon, polycrystalline silicon, and thin film cells (namely amorphous silicon cells).

These three technologies perform differently under operation: of the three, monocrystalline technology shows the highest efficiency, followed by polycrystalline silicon and lastly amorphous silicon thin film cells. However, amorphous silicon cells are the ones that perform best under low light conditions. Lastly, when observing the performance of the three types of cells under increasing radiance and temperature, polycrystalline cells are the ones less affected by these circumstances [55]-[57].

Each of these aspects are fundamental when designing a PV system, since climatic conditions will affect solar cell technologies differently. Campo Loro is located in the Aw Köppen-Geiger climate classification region of the Paraguayan Gran Chaco [58]. This implies that its climate is characterized by all year round hot weather (the mean temperature of the coldest month is over 18°C) and a pronounced dry season, with the driest month having less than 60 mm of precipitation and also less than $(100 - \frac{mean\ annual\ temperature}{25})$ [58]. Because of its high temperatures and irradiance throughout the year, and low precipitation (thus having few cloudy days), the best technology to install in Campo Loro seems to be the polycrystalline cells, which will suffer less and perform the best under these climatic conditions.

4.3.1.2. Calculations

For the study of solar panel operation, one of the most important characteristics to analyze is their I-V curves. In Figure 17, the typical appearance of a solar panel's or solar cell's IV and power curves is shown. Standard characterization of solar panels by manufacturers is done under Standard Test Conditions (STC), which are AM1.5, an irradiance of 1000 W/m^2 and cell temperature of 25°C. In the technical data sheets of solar panels, the main parameters obtained from IV curve characterization are given: its short circuit current, (I_{SC}), open circuit voltage (V_{OC}), maximum power voltage (V_{MP}) and maximum power current (I_{MP}).

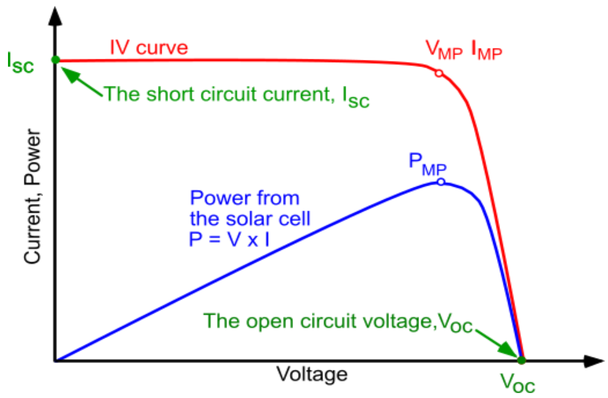


Figure 17. Typical IV and Power curves of a solar cell [59].

The maximum power produced by a solar cell is:

$$P_{MP} = V_{MP}I_{MP} \qquad \textit{Eq. 1}$$

And the efficiency of the solar cell is, then:

$$\eta = \frac{P_{MP}}{P_{in}} \qquad \textit{Eq. 2}$$

Where P_{in} (incident power) is the result of multiplying the irradiance of the location where the solar panel is installed times the area of the solar panel. In the IV curve characterized by manufacturers, the irradiance is 1000 W/m^2, and the values of V_{MP} and I_{MP} given in the solar panel's technical data sheet are only valid under that irradiance. However, under other irradiation conditions, IV curves change. When the irradiance the solar panel is receiving is lower than 1000 W/m^2, the panel's short circuit current quickly decreases, as seen in Figure 18. Thus, with less irradiance, the solar cell generates less power.

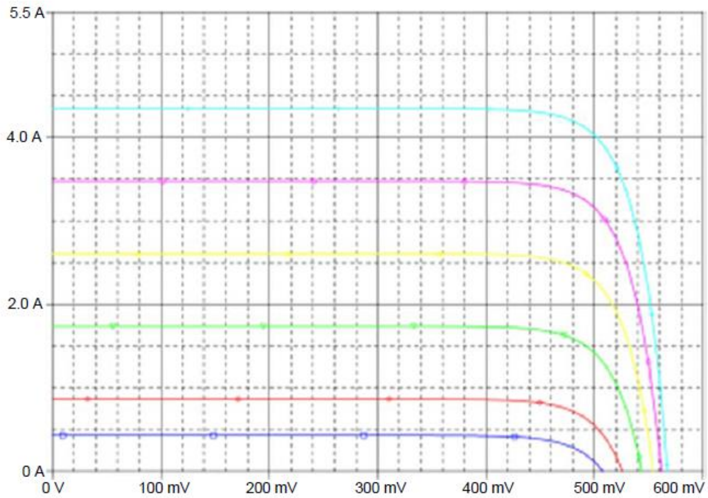


Figure 18. Variation of a solar panel's IV curve with different irradiance values (from top to bottom: 1000 W/m^2, 800 W/m^2, 600 W/m^2, 400 W/m^2, 200 W/m^2, and 100 W/m^2) [60].

Solar panel data sheets do not usually include the values of V_{MP} and I_{MP} at different irradiance conditions. However, they do include its tested efficiency under STC. Assuming the efficiency of the solar panel remains constant throughout different irradiance conditions is acceptable, and thus calculating the power generated at different irradiance values can be done using Eq. 3.

$$P_{MP} = \eta \, GHI_t \, A_{panel} \qquad \text{Eq. 3}$$

Where $\mathrm{GHI_t}$ is the irradiance value at a given moment t and $\mathrm{A_{panel}}$ is the area of the solar panel.

4.3.2. Battery storage

4.3.2.1. Description and context

Many times, batteries as a source of energy storage are considered when designing solar PV systems, due to the irregularity and certain degree of unpredictability that daily irradiation presents. Different types of batteries are adequate for different applications. For our study, the chosen batteries are the absorbent glass mat (AGM) type.

AGM batteries are lead acid batteries where the electrolyte is absorbed in a very thin fiberglass mat or mesh, that is placed between the two battery plates, compressed, and welded. The electrolyte is thus immobilized, which makes the battery spill-proof and able to be stored in various positions and locations. Compared to flooded and conventional lead acid batteries, AGM batteries present less dangers related to operation and environmental pollution, as they do not release toxic fumes and, in case of damage, the amount of electrolyte that could be released is very small. They also require much less maintenance and withstand temperature better than conventional lead acid batteries, but are more expensive than these, although still cheaper than other low maintenance technologies such as lithium ion [61], [62]. Due to these characteristics, AGM batteries are considered for this design where applicable.

4.3.2.2. Calculations

The only aspect of battery behavior that needs to be considered in this design is the amount of energy that is stored in them at each moment. Energy available at the batteries will depend on the supply from the solar panels, and on the energy being consumed by the water treatment units. Depending on the irradiation conditions and the state of the desalinated and groundwater tanks, the batteries will be charging, discharging or doing both at the same time: that is, they may be receiving energy from the solar panels, powering the water treatment units, or doing none of those things, or only two at the same time.

$$E_{bat}(t) = E_{bat}(t-1) + E_{PV} - \Delta t \, (P_{desal} + P_{disinf}) \qquad \text{Eq. 4}$$

Where $E_{bat}(t-1)$ is the energy stored in the battery in the previous calculated moment, Δt is the amount of time that has passed between the t and $t-1$, E_{PV} is the energy generated by the solar panels, P_{desal} is the power required by the desalination unit, and P_{disinf} is the power consumed by the disinfection unit.

4.3.3. EDR desalination and electrochemical water disinfection

The two main treatments that the brackish groundwater of Campo Loro must be subjected to make it suitable for the village's water needs are: desalination and purification. The technologies chosen for these two purposes, which are EDR desalination and electrochemical water disinfection, are explained in this section.

4.3.3.1. Description and context

Desalination is the process through which salts are removed from saline water by inputting a certain amount of energy and obtaining two separate streams: a low salinity stream and a stream of salty brine. Its applications vary greatly depending on the intended salinity of the product stream, but due to increased levels of water stress across the world, with approximately 4 billion people experiencing severe water scarcity nowadays at least one month a year, and an estimated 700 million people being displaced because of intense water scarcity by 2030 [18], one of the main focus of this area of knowledge has been on using desalination to produce drinking water.

Salinity is often described in terms of TDS (total dissolved solids), either in mg/L or ppm. Acceptable drinking water is usually in the range of 300 – 600 mg/L, while saline water sources are classified as having a salinity equal or greater than 1,000 mg/L [63]. The best desalination technology for a desired application will be the one capable of producing the highest volume of product stream, at the expense of a small volume of salty brine and a minimal amount of energy.

One of the methods to classify desalination technologies is by the working principle that achieves saline water separation. This divides desalination processes in 3 categories: thermal, membrane-based, and charge-based desalination [63].

Table 4. Desalination technologies divided in 3 categories by their working principle. Table created with information from [63].

Category	Description	Main examples
Thermal	Use of heat to induce phase changes in the feed water stream, evaporating and then condensing it, so that fresh water is produced.	Multiple effect-distillation (MED), multi-stage flash distillation (MSF), solar still distillation.
Membrane-based	A thin film of a semi-permeable material physically separates salt from water when the saline stream passes through it.	Reverse osmosis (RO)
Charge-based	Salt ions diluted in the saline water stream are separated by applying a small electric potential, which attracts positive and negative charged ions in opposite directions, and using various channels separated by cation- and anion-exchange membranes.	Electrodialysis (ED), electrodialysis reversal (EDR), membrane capacitive deionization (mCDI).

The technologies shown in the table above are in different stages of commercialization or study and are adequate for different ranges of operation. Thermal technologies such as MSF and

MED are best suited for desalinating high salinity sources (> 35,000 mg/L) at high capacities (> 3,000 m^3/day) and have been widely commercialized for decades, while solar still distillation is only feasible for very low production capacities (5-10 L/m^2day) and higher productivities are still being developed. Reverse osmosis is widely available in the market and is suited for household, community, and industrial applications, making it quite versatile. Charge-based technologies are optimized for low-salinity brackish water sources in a wide range of production capacities, but are not as commercialized as RO for drinking water treatment [63], [64].

To desalinate the volume of water required for Campo Loro, RO and EDR (which is the most mature out of all the charge-based processes) seem the best choices: both are capable of desalinating low-salinity water sources (< 3,500 mg/L) at a production rate of 5-10 m^3/day. However, RO needs higher quantities of energy than EDR to treat water sources with < 3,500 mg/L, and it generally has a much lower water recovery rate (the percentage of feed water transformed to fresh water), with 25-50% for RO and approx. 80% for EDR systems [63]. Additionally, pre-treatment stages are usually required for RO and its operating costs are often higher because its membranes are more prone to fouling. Thus, despite EDR being less commercially available than RO, it seems the most suited technology for our desired application.

In the EDR process, saline feed water is circulated through an electrodialysis stack composed of alternating cation- and anion- exchange membranes and bounded by two electrodes. As their names suggest, anion-exchange membranes only allow anions to pass through them, while cation-exchange membranes are cation-selective. When a voltage is applied across the stack, anions are drawn towards the anode and cathodes move towards the cathode. Depending on the type of membrane they encounter in their path, ions are either able to cross them or not, creating alternating channels of fresh water and brine [63], [65]. After a certain period, the voltage applied to the stack is reversed so that any salt or organic compound that has accumulated on the membranes' surface is detached and dissolved back into the streams, prolonging membrane life.

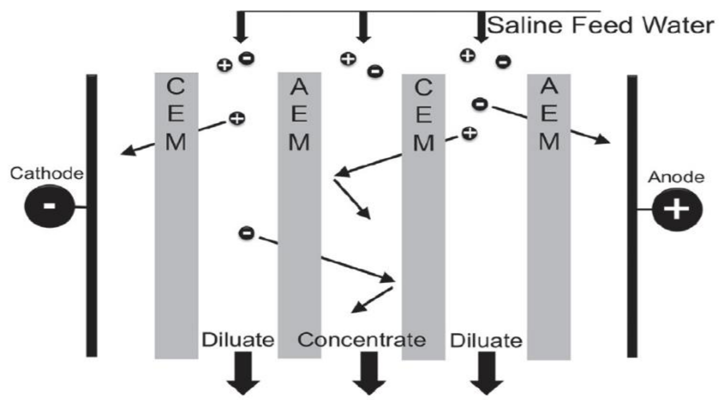


Figure 19. Schematic of the EDR process [65]. Here, the freshwater stream produced by the system is called diluate, while the brine stream is the concentrate.

EDR processes need a DC power supply to carry out the desalination, which makes them especially suitable to be powered by PV solar systems. Additionally, PV is the most appropriate renewable energy technology to pair desalination with if possible due to the natural relationship between requirement of water and the availability of solar power.

On the other hand, post-treatment is necessary to ensure that the desalinated water meets all the required standards for consumption. For our system, disinfection may be necessary because the desalinated water will be stored in tanks, and thus water-borne pathogens may arise. For this purpose, the electrochemical water disinfection (EWD) prototype designed by the Sustainable Energy Applications Group of the University of Santiago de Compostela has been selected. It is made of globally purchasable materials and elements, it can disinfect a wide range of potable waters, and its operation is extremely simple [66], [67], making it the perfect technology to apply in a project such as this one.

4.3.3.2. Calculations

To adequately calculate the performance of the desalination process in an EDR stack, the model created by Wright et al. [65] described in **Annex C** is recommended. Modelling the system using these equations would be the preferred approach to calculate what the optimum number of cell pairs, voltage, and flow for the diluate and concentrate streams are, so that the optimum EDR system could be accurately designed. However, as was explained in section **4.2**, many of the initial values (of groundwater concentration, daily water consumption, etc.) used in the design described in this work are either estimated or rounded off based on available information. Thus, such a detailed and precise approach is not desirable at the moment. For this work, the power required for the EDR system to desalinate the required desalinated water flows for Campo Loro from 3,500 mg/L to below 500 mg/L was estimated based on the available information found in scientific publications of similar nature to this master's thesis [50], [68]-[72]. The same was done for the power required by the disinfection unit [66], [67].

4.3.4. Groundwater pump

4.3.4.1. Description and context

The most common type of pump used in PV solar pumping systems for town and city water supply is the deep well submersible pump [73]. They are usually characterized by their easy installation, high discharge and heads, no exposure to climate and no priming nor cavitation [73], [74]. It is a type of deep well pumps, which are designed to operate underground and completely submerged in water, which separates them from surface mounted pumps, installed near the water surface. A submersible pump is composed by multiple stages of centrifugal pumps, all driven by a single shaft moved by a motor. The motor driving the pump may be AC or DC. For our study, a DC motor is used to simplify the connections to the PV solar system.

4.3.4.2. Calculations

The main aspect of the pump that needs to be modelled for our design is the volume of water it can pump with available power. This can be calculated with the following equation:

$$P_{pump} = \rho g Q H \qquad \text{Eq. 5}$$

Where ρ is water density (kg/m³), Q is the flow rate of the pump (m³/s), H the hydraulic head (in m) and g the gravity acceleration (in m²/s).

No information is available on the depth of the groundwater of Campo Loro. Thus, for our design we have considered 50 m for the hydraulic head. The pump that will be used is the IDEAL Triton SJI8 0.75CV pump, which is capable of pumping 2 m³/h at 50 m with a power consumption of 550 W [75]. It must be noted that, although we have considered a hydraulic head of 50 m in our design, this pump is capable of operating with up to 200 m of hydraulic head, thus allowing flexibility if the general design needs to be changed in the future.

With this data, we're able to calculate the efficiency of the pump, which is:

$$\eta_{pump} = \frac{\frac{2\,m^3/h}{3600\,s/h} \cdot 50\,m \cdot 1000\,\frac{kg}{m^3} \cdot 9.81\,\frac{m}{s^2}}{550\,W} = 0.495 \quad \text{Eq. 6}$$

It then allows us to calculate the flow of pumped water as a function of incident irradiation:

$$Q = \frac{P_{in} \cdot \eta_{pump} \cdot \eta_{losses}}{50\,m \cdot 1000\,\frac{kg}{m^3} \cdot 9{,}81\,\frac{m}{s^2}} \quad \text{Eq. 7}$$

Where η_{losses} is considered 0.9 and represents losses due to friction, and P_{in} is the incident power (irradiance times the area of solar panels to power the groundwater pump).

4.4. Methodology for design

After selecting the technologies, the remaining step is defining the methodology followed to design the system. For this purpose, we must revisit the two radiation data sets that have been used to assess the solar resource in Campo Loro. The average solar irradiance in the two solstices from both data sets is shown in Figures 20 and 21.

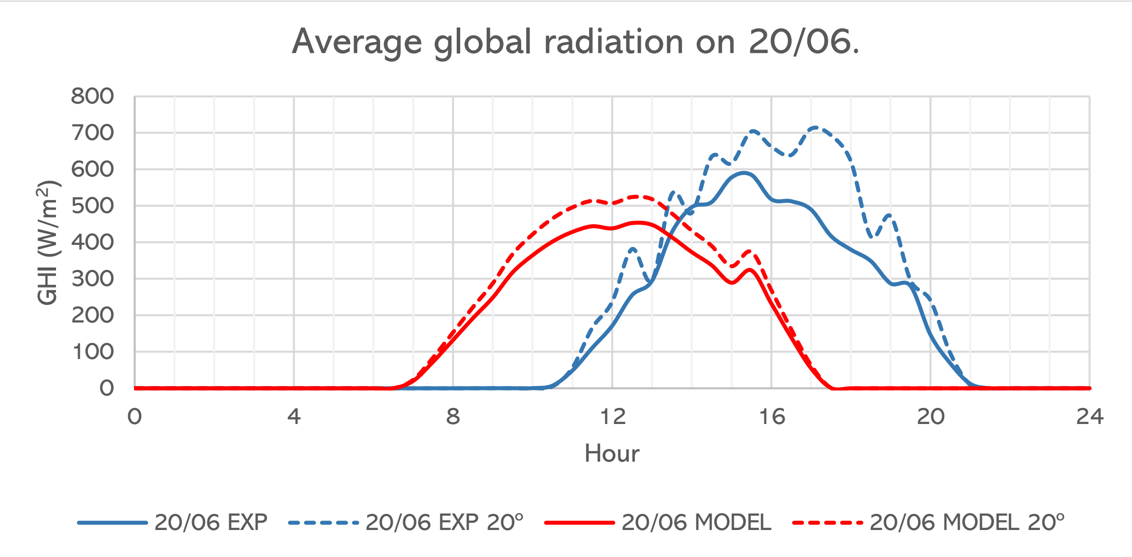


Figure 20. Global average radiation on the winter solstice on a horizontal and 20° angle surfaces. Modelled data from NSRDB-PSM model [52] and experimental data from the Meteorology Department from the National University of Asunción.

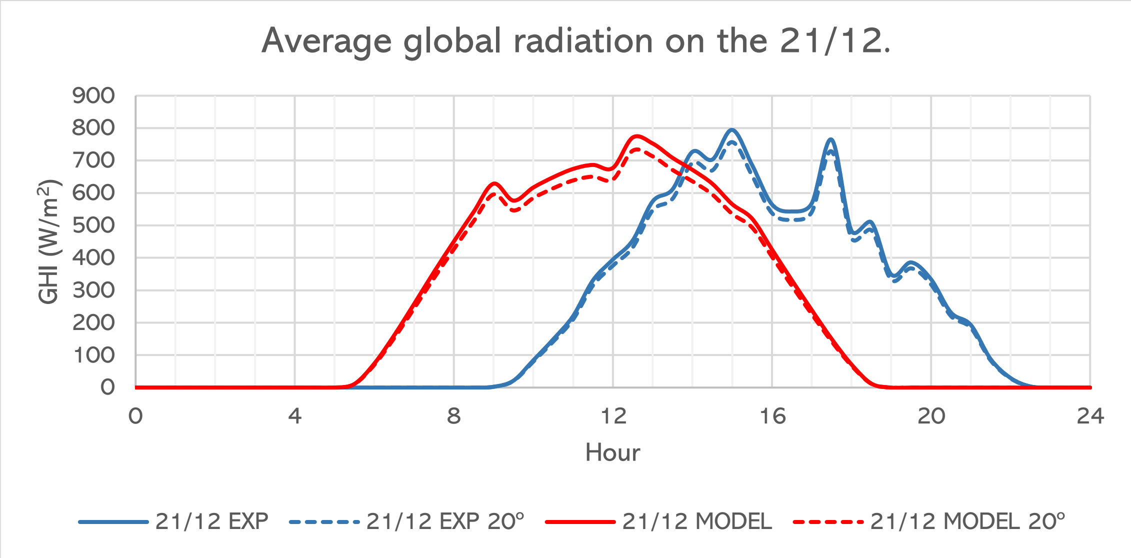


Figure 21. Global average radiation on the summer solstice on a horizontal and 20° angle surfaces. Modelled data from NSRDB-PSM model [52] and experimental data from the Meteorology Department from the National University of Asunción.

The two data sets are fairly different from one another. It was already visible in Figure 16 (section **4.3.1**) that the monthly average daily radiation is higher on the model data set than on the experimental one in almost every month. Other noticeable differences are also visible when comparing daily radiation in Figures 20 and 21: between the two data sets there is a horizontal displacement of 4 hours, which is probably due to differences in the used time zones when recording the data. On the other hand, in both graphs, the experimental values show a bigger variation, while the model data set presents a more stable tendency throughout the day. Additionally, the peak daily radiation value is higher in the experimental data than in the modelled one during both solstices, although the difference is remarkably wider during the 20th of June. However, as monthly average radiation in Figure 16 shows higher values for the model data set on average, this might indicate that the experimental data set presents higher variations of daily radiation throughout the month. This is important to consider when designing a PV solar system, as high variations usually mean bigger amounts of energy storage when supplying to a constant demand.

Due to these differences in radiation data, the optimized system design process is repeated 3 times under the different radiation conditions described below. By doing so, we will be able to infer how affected the design of the system is by the chosen radiation data and select the system that can best ensure the needed water supply.

I. The system is designed using the annual average GHI model data in intervals of 30 minutes (by averaging the data from 2010 to 2018).
II. The system is designed using the annual average GHI experimental data in intervals of 30 minutes.
III. The system is designed using the GHI model data in intervals of 30 minutes from 2010 to 2018.

In each of these three radiation scenarios, two system configurations are proposed for study. Both configurations are composed by: a PV energy generation system that powers a desalination unit and a disinfection unit; a groundwater pump, powered by its own PV system;

2 water pumps (for filling/emptying tanks); and 3 tanks (one for the pumped groundwater, another for desalinated water, and a third for desalinated and disinfected water). The only difference between the two configurations is the presence (A) or absence (B) of batteries as a means of energy storage. The weight of the variations of daily irradiation in both configurations will be taken by the water tanks as much as possible, as batteries are expensive and require maintenance, and a correctly designed water tank can act as an energy storage unit as well.

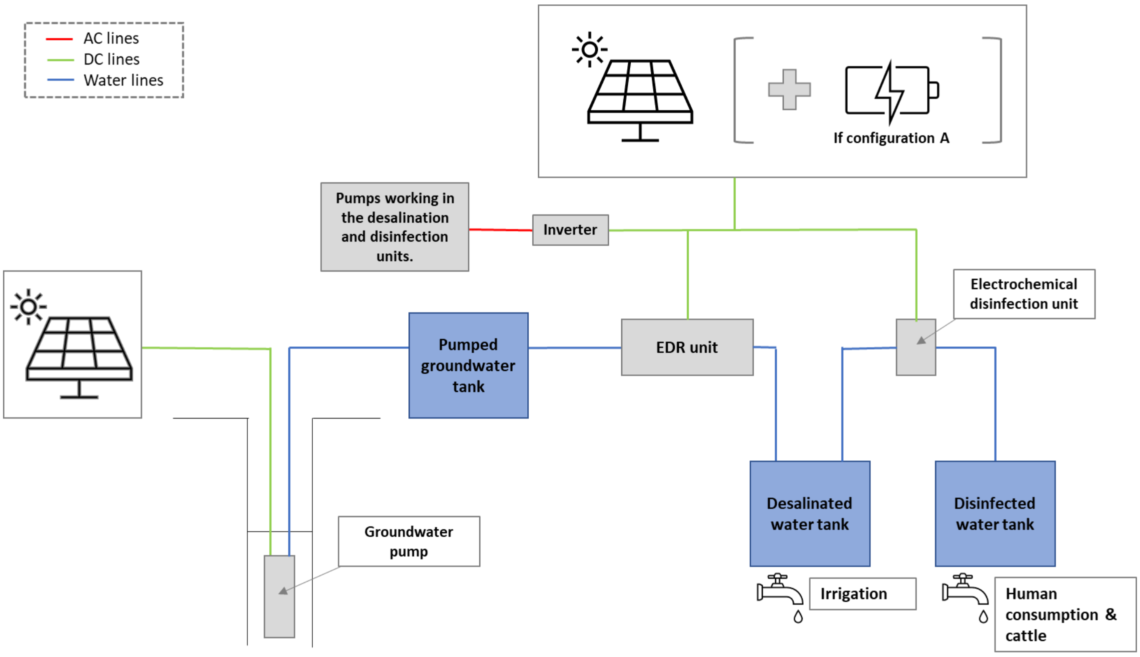


Figure 22. Diagram of the system under configurations A and B.

Because the two configurations will be considered under the three radiation scenarios, in reality there will be 6 system designs, each optimized under the considered conditions.

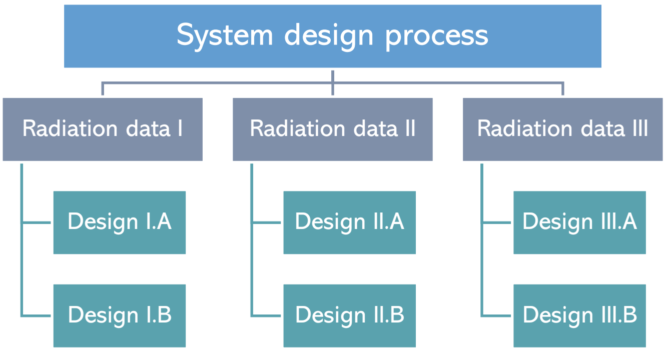


Figure 23. The 6 system designs considered in the design process, as a result of optimizing 2 system configurations under 3 radiation data sets.

The optimization of the system is done as follows (both for configuration A and B) under the three scenarios:

1. Values of number of solar panels, desalinated tank volume, pumped water tank volume and battery capacity (only applicable to configuration A) are set.
2. The operation of the system following its corresponding logic tree is run under radiation conditions I, II and III. At the beginning of each run, the desalinated and groundwater tanks are considered full.

3. Steps 1 and 2 are repeated until the optimum system is found, which must:
    a. Use the minimum amount of (in order of priority): batteries (if applicable), solar panels, and tank volumes.
    b. For radiation conditions I and II, the loss of load throughout the year must be 0%. That is, the consumption needs of Campo Loro must always be met.
    c. For radiation conditions III, the loss of load throughout the 9 years must be 0,1%. That is, the consumption needs of Campo Loro must be met 99,9% of the time throughout the entire data set.

A summary of the design process is shown in Figure 24.

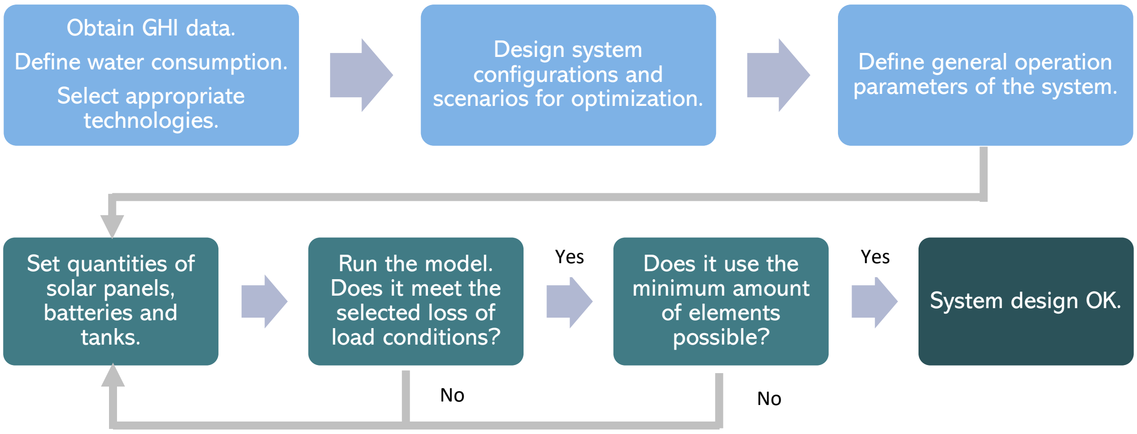


Figure 24. Diagram summarizing the system design process.

The remaining aspects that need to be defined are some general parameters and details on how the system will operate. Namely:

1. Logic tree the system will follow when operating,
2. Power consumptions and mode of operation of the components,
3. The water consumption pattern of Campo Loro.

Firstly, the logic trees for the system are as shown in Figures 25, 26 and 27.

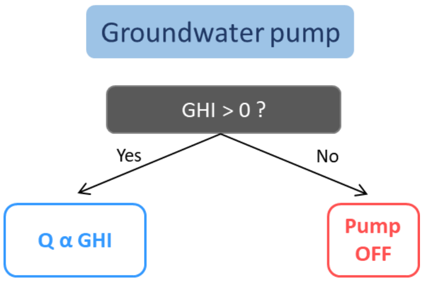


Figure 25. Logic tree that describes the operation of the groundwater pump.

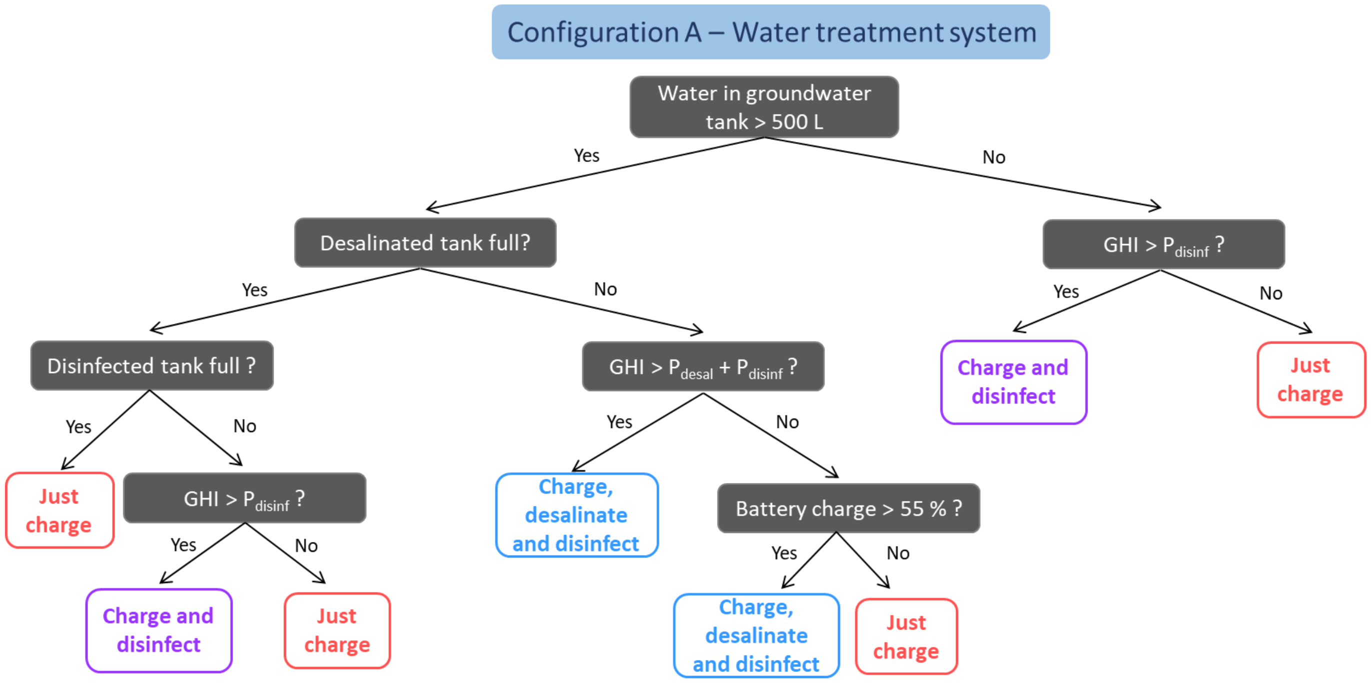


Figure 26. Logic tree that describes de operation of configuration A.

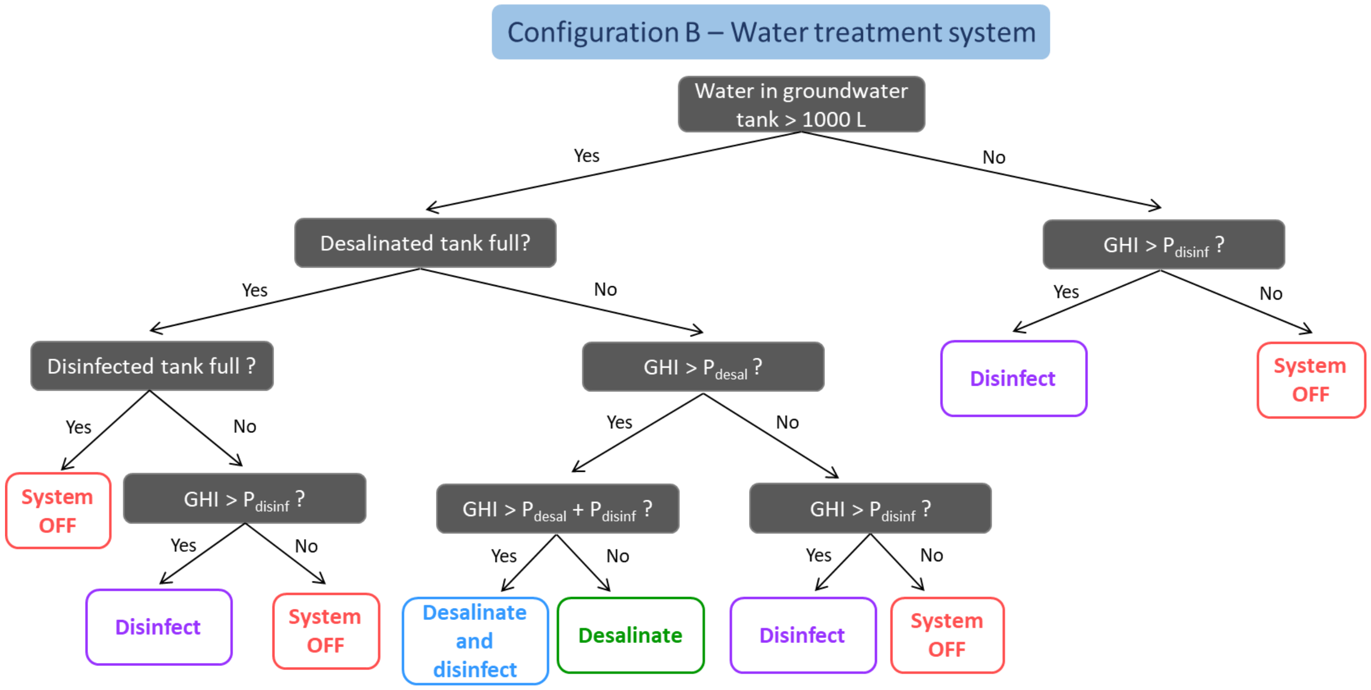


Figure 27. Logic tree that describes de operation of configuration B.

In configuration A, the desalination and disinfection units are activated or deactivated at the same time and are set to work only for 11.5 hours each day. In configuration B, the desalination unit is free to work whenever it can due to irradiation conditions, while the disinfection unit is set to work only for 8.5 hours each day. This has been established because the disinfection unit removes water from the desalinated water tank, and if it is left to work whenever it can, it will empty the desalinated water tank frequently, leaving no water for irrigation. On the other hand, the groundwater pump in both configurations works independently from the rest of the system, as it has its own PV system. Its flow varies depending on available radiation.

Secondly, the power consumptions and mode of operation of the desalination and disinfection units need to be set. Table 5 provides details on their operation (power consumptions were already mentioned in section **4.3.3.2** and are repeated here). Both elements will operate in batch mode in periods of 30 minutes and 1 minute, respectively.

Table 5. Power consumption and batch parameters for the desalination and disinfection units.

EDR unit	
Configuration A	
Batch size	455 L
Batch duration	5 min pumping + 25 min desalinating
Expected desalination rate	910 L/h
Power consumption	2000 W
Configuration B	
Batch size	625 L
Batch duration	5 min pumping + 25 min desalinating
Expected desalination rate	1250 L/h
Power consumption	2500 W

Electrochemical disinfection unit	
Configuration A	
Batch size	7.5 L
Batch duration	1 min
Expected desalination rate	455 L/h
Power consumption	100 W
Configuration B	
Batch size	10.5 L
Batch duration	1 min
Expected desalination rate	625 L/h
Power consumption	150 W

Observing what was described for the logic trees, configuration A will thus desalinate 10.5 m^3 and disinfect 5.25 m^3 approximately (as both units will work 11.5 hours daily if there is sufficient radiation or if the batteries are not discharged). Configuration B will desalinate as much as possible daily with the available power from the solar panels and disinfect approximately 5.25 m^3 (as the disinfection unit can only work during a period of 8.5 hours during the day). Both units produce more water than what is needed daily if able to work without stopping due to insufficient radiation or energy in the batteries. This has been done to enhance water storage and help buffer the variations of daily radiation.

Lastly, the consumption pattern of Campo Loro is not considered constant throughout the day. Additionally, the consumed water is not always extracted from the same tank: we have considered that the amount of water for human consumption and the amount for cattle consumption are extracted from the potable water tank, while the volume for irrigation is extracted from the desalinated (but not disinfected) water tank. The consumption pattern is shown below.

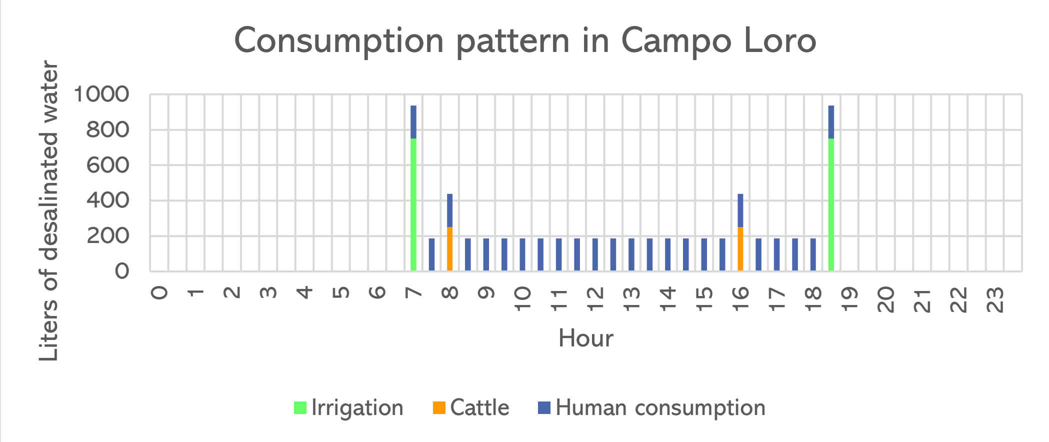


Figure 28. Considered consumption pattern. The four-hour difference between experimental and model data was considered in the consumption pattern when working with the experimental data as well.

4.5. Final design

The results of optimizing configurations A and B under radiation conditions I, II and III are presented in Table 6. Calculations for the number of solar panels were done using the technical data available for the ERA polycrystalline 340 Wp, 24 V solar panel, whilst the number of batteries was calculated using the Ultracell UC-138-12 battery (138 Ah, 12 V) as reference.

Table 6. Results obtained for the six designs.

	Design I.A	Design II.A	Design III.A	Design I.B	Design II.B	Design III.B
Solar panels for water treatment	22	25	28	29	40	48
Batteries	4	4	6			
Solar panels for pump	4	4	5	4	4	4
Desalinated water tank (m^3)	45	50	55	45	60	65
Disinfected water tank (m^3)	40	47	55	5	8	10
Groundwater water tank (m^3)	4	5	10	4	5	10

As was expected, the results between both configurations and between the three different radiation conditions are fairly different. The desalinated tank and disinfected tank volumes were maximized in the designs to allow for smaller quantities of solar panels and batteries. There are not many differences between the values for the desalinated tank (45 – 65 m^3) in both configurations, but the disinfected water tanks for configuration A are much larger than for configuration B. This is because in configuration B the disinfection unit will work if there is enough irradiation to power it, even if it is not enough to power the desalination process. Thus, it is less affected by low radiation months. On the other hand, the groundwater tanks are very similar in both configurations, increasing in size with the variability of daily radiation (4 – 10 m^3). The solar panels required to power the groundwater pump are also almost the same in the 6 designs (4 – 5 panels).

The area of solar panels for water treatment increases with rising variability of solar radiation conditions: the area needed under radiation conditions II and III for configuration A is 15% and 30% higher, respectively, than for radiation data set I; while for configuration B the increments are 25% and 50%. This is easily explainable, as data set I is composed of the average modelled radiation of 9 years. Averaging almost a decade of values helps even out yearly variations that are more present in data sets II and III: data set II is also an average, but only of 4 years' worth of data and with 45% of the values missing; data set III, on the other hand, makes the system work continuously through nine years of modelled data, checking if it withstands the unbuffered yearly variations, which are quite apparent between some of the years (see Figure 29).

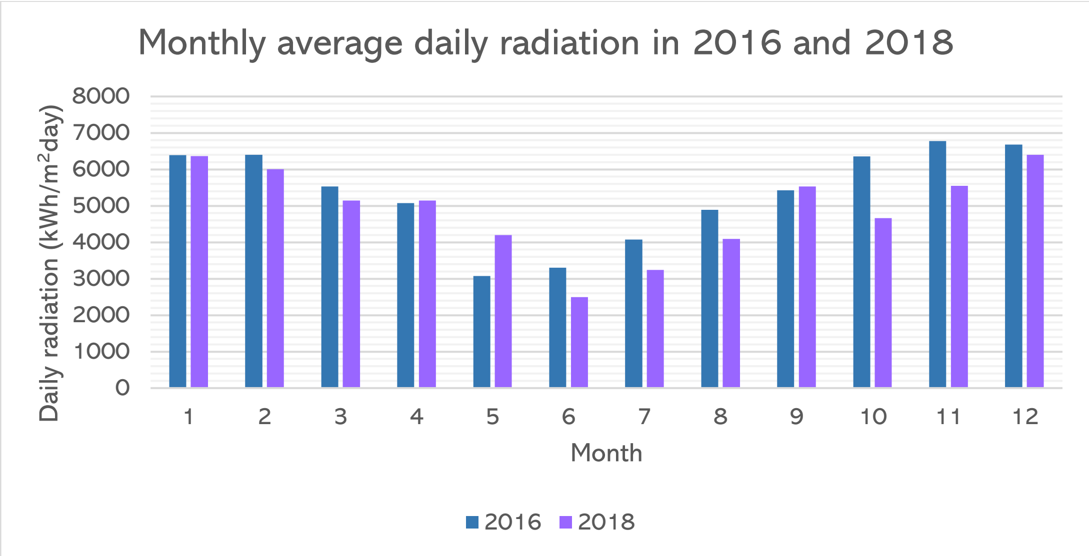


Figure 29. Comparison of the monthly average daily radiation in 2016 and 2018.

This variability also affects the battery capacity needed in configuration A, but in a lesser way, as during the optimization an increase in solar panels and volume of tanks was preferred over an increase in battery capacity.

As we want to be able to ensure that the water consumption in Campo Loro is met, due to the importance that water undoubtedly has in the well-being of a community, the best choice would be to choose the systems obtained from optimizing under the III data set, as they consider the operation of the system for a longer period. Although the location of the data extracted from the NSRDB-PSM model is further away from Campo Loro than the experimental data (155 km vs 50 km), the bigger availability of reliable data allows for modelling the behavior of the system for longer, which makes for a more realistic approach to the optimization of the system. The two systems obtained from the III data set are clearly the biggest out of the rest of the results, but they are the safest choice.

The total costs for the two configurations under data set III are shown in Table 7 (to see a detailed description of the budget, see **Annex C**). The capital costs and operating costs for configuration B are lower than for configuration A. This is because configuration A needs bigger volumes for its water tanks, which increases capital costs, and it also has batteries that need to be replaced every 5 years, incrementing the operating costs. When comparing the cost per m^3 of desalinated water, configuration B is clearly favored. Therefore, the most suitable optimized system is the one calculated under radiation conditions III in configuration B, composed by a total of **52 solar panels, a 65 m^3 desalinated water tank, a 10 m^3 disinfected water tank, and a volume of 10 m^3 for the groundwater tank**.

Table 7. Comparison of the costs associated with designs III.A and III.B.

	Design III.A	Design III.B
Capital costs (€)	35,073.83	32,357.81
Operating costs (20 years) (€)	18,151.02	14,400.00
Volume of treated water in 20 years (m^3)	73,000	73,000
Price of treated water (€/ m^3)	0.73	0.64

Table 8. Comparison of the price of treated water and CO2 emissions of the three considered power supply sources.

	Design III.B	National grid	Diesel generator
Price of treated water (€/ m^3)	0.64	0.73[2]	0.91[3]
Associated emissions of CO_2 (ton)	0	0	100[4]

The operation of this system III.B through data set III is shown in **Annex D**.

Lastly, a comparison of the costs associated with a water pumping and treatment system to meet the needs of Campo Loro using different energy supply sources has been made. That is, we have compared the costs of the same water treatment and pumping system but, instead of being powered by a solar PV system, powered by electricity from the Paraguayan grid or by a diesel generator. The results are given in Table 8. As can be observed, the costs per m^3 of desalinated water for a system supplied by the grid or by a diesel generator are higher than for the designed system with 52 solar panels. The solar PV system is even more favored than the other two, apart from the costs per m^3 of desalinated water, due to three main issues:

1. The costs associated with a system supplied by the electricity grid are similar to the costs of a solar PV powered system. Supplying the system with the grid would provide more reliability and stability than solar panels, whose operation heavily depends on meteorological conditions. However, the electrification of the Paraguayan Gran Chaco is still very low. Campo Loro has some of its houses connected to the grid, but adequate maintenance of the electrical systems is still questionable. Paying the electrical bill each month could also rise problems, especially because Campo Loro would not be eligible for the Social Rate established by the Paraguayan government due to the high consumption of the desalination system [76].
2. Powering the system with a diesel generator could create a possible dependency on diesel supply, which could be detrimental for the community: both the price fluctuation and the nearby availability of diesel could put the reliable and stable supply of potable water at risk.

[2] Price of kWh supplied by the electricity grid obtained from [76].
[3] Price per liter of diesel in Paraguay obtained from [77].
[4] Associated emissions per liter of diesel obtained from [78]

3. Electricity generation with diesel has an associated amount of CO_2 emissions into the atmosphere that must not be discarded: to power this system, it would emit 100 ton of CO_2. This makes it a less environmentally sustainable option in comparison to the others, as solar panels emit no CO_2 during their operative life, (a Life Cycle analysis that would consider the greenhouse gases emissions associated to their manufacture is out of the scope of this work); on the other hand, in Paraguay 99,93% of the national electrical demand is supplied by renewable energies (namely hydropower) [79]. Therefore connecting the system to the grid would have almost zero associated CO_2 emissions as well.

Thus, the most adequate system clearly remains **design III.B**, even when compared to the simpler energy generating options mentioned above.

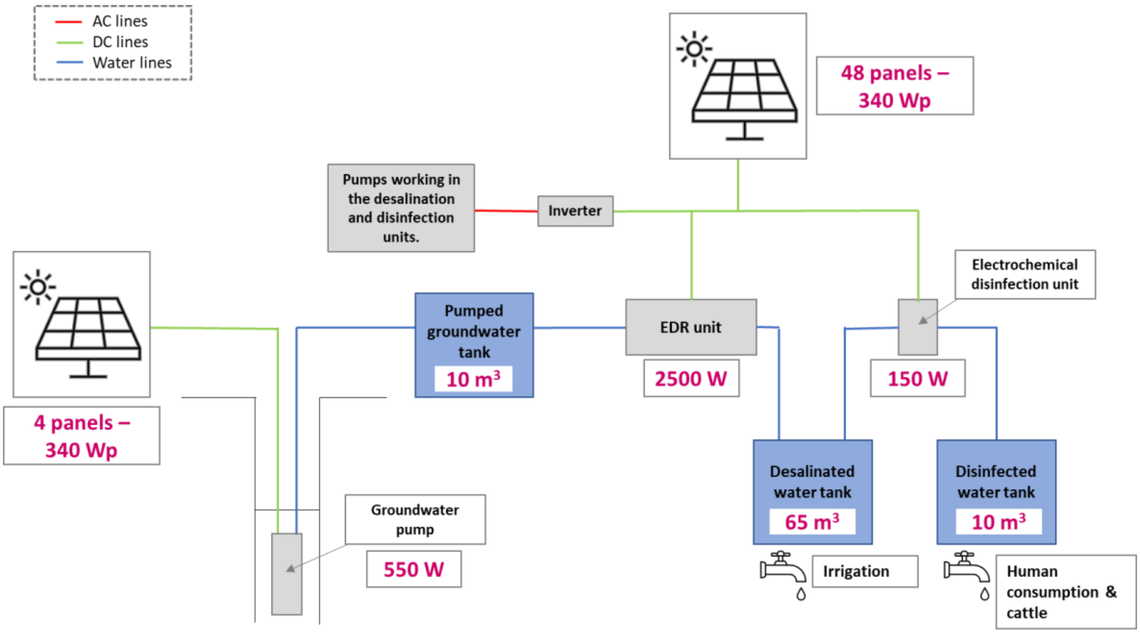


Figure 30. Resulting design of the water pumping and treatment system for Campo Loro.

5. Implementation

As has been explained, collecting detailed data on the groundwater composition of Campo Loro was not possible, and thus much of the information that has been used in this design has been searched or estimated considering available literature. Therefore, the final design detailed in the previous chapter must be considered as an **initial design**, that will be modified as more direct information is gathered. This is especially important to consider as other parts of the Chaco (namely the Chaco province of Argentina) have high levels of arsenic [80]. If this element were found in the groundwater of Campo Loro, the system would need to be thoroughly redesigned to include more processes to convert the groundwater to potable water.

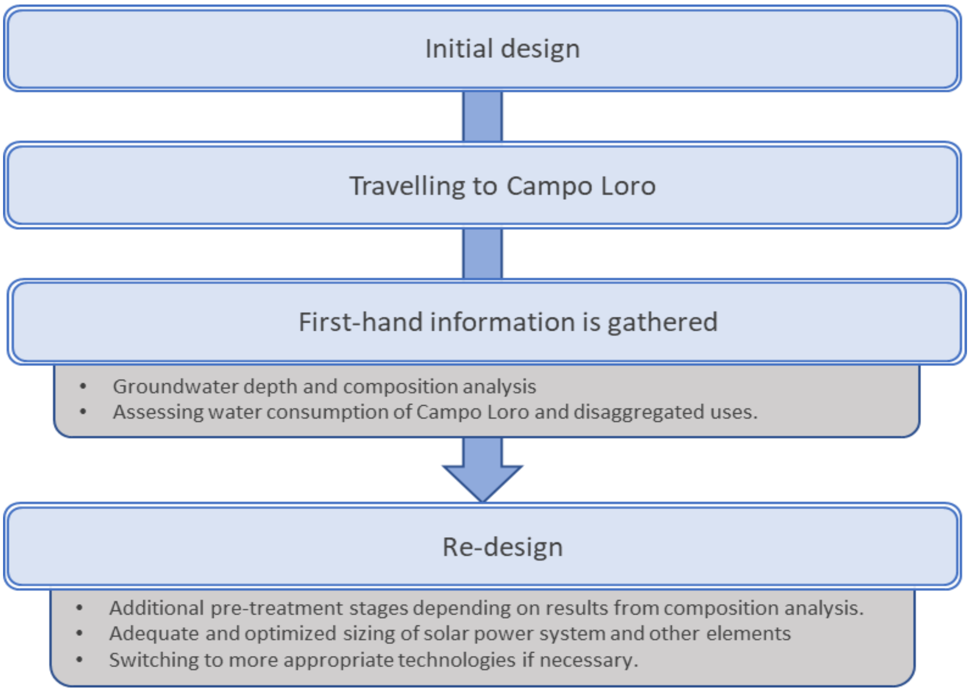


Figure 31. The system must be re-designed once more accurate information is gathered.

The first step that must be taken after this design is to reschedule the trip to Campo Loro that was planned for April of this same year (2020), once it is safe to do so due to COVID-19. In that trip, more in-depth information will be gathered, including taking measurements of the composition of Campo Loro's groundwater, as well as its depth and well characteristics. A more detailed disaggregation of the population's water consumption patterns and quantities will be requested as well, to further clarify the volumes of water the water treatment units should be capable of producing for the population.

Another important aspect that must be discussed with the population as well is brine disposal. About 20% of the pumped groundwater is turned into brine during the desalination process, which must be disposed of as it accumulates over time. In Campo Loro's case, the two most suitable options for brine disposal are either evaporating it in evaporation ponds or using it for agricultural irrigation. Evaporating brine from brackish water desalination could prove slightly difficult, as a large area is needed and this kind of brine tends to have a low salinity, so evaporating it to solid salt is harder. On the other hand, using it for agricultural irrigation would require using salt tolerant crops and detailed control on the amount of brine used to irrigate the plants. Leaching may also need to be used [81]. However, although perhaps more labor inducing, this option could help increase both the quantity and variety of crops in Campo Loro. The selection of the most adequate crops must be discussed with the community if this option is chosen.

In this first trip, a small prototype of a solar PV system with desalination and/or disinfection units will also perhaps be installed to test how they would work in the location.

From then on, a better assessment and design of the appropriate water pumping and treatment system for Campo Loro can be thought out. It would follow the methodology described for this first design but changing the initial considered conditions with the new information gathered during the trip. Especial attention will need to be paid to additional pre-treatment stages that may have to be implemented depending on the results of the groundwater composition of Campo Loro. A list of the possible pre-treatments depending on the problems found in the groundwater are detailed in Table 9. Other treatments, either pre or post desalination, such as arsenic removal, must also be considered if necessary.

Table 9. Membrane foulants and types of pre-treatment [63].

Type of fouling	Foulant	Appropriate pre-treatment
Biological	Bacteria, micro-organisms, viruses, protozoa	Chlorination
Particle	Sand, clay	Filtration
Colloidal	Organic and inorganic complexes, micro-algae	Coagulation + filtration
Organic	Natural organic matter (NOM), humic and fulvic acids, biopolymers	Coagulation + filtration + activated carbon adsorption + ultra-filtration
Mineral	Calcium, carbonates, magnesium barium or strontium sulphates	Anti-scaling dosing, acidification
Oxidant	Chlorine, ozone	Sodium bisulphite, metabisulphite, activated carbon

After redesigning the system and purchasing and gathering the necessary materials and components, another trip to Campo Loro must be made to completely install the system. Approximately a week should be needed to completely set it up and then it should be started up and left running for as long as needed to fill up the desalinated, disinfected and pumping tanks completely. This is so the system starts to be used with the three tanks full, since that is what is considered under our assumptions when designing the system. While filling up the tanks, classes and training on operation and maintenance of the system must be given to members of the population of Campo Loro.

Once ready, the system would begin operating normally. Follow-up and data gathering will continue to be performed to ensure optimal operation of system.

During the re-design and implementation of this system, other activities, systems, or technologies may be included in the Goodwill Action in Campo Loro. This has yet to be determined, depending on the information transmitted to us during the first contact with the target community.

Lastly, depending on the outcome of the implementation of the Goodwill Action, the relationship built with the community and the availability of funds, the cooperative work that has started with this master's thesis could continue with the full development of a Sustainable Community in Campo Loro under the Sustainable Community Project of CLRLA-UNESCO.

6. Conclusions

In this work, the first stage of the development of a Goodwill Action in the community of Campo Loro was studied. The optimal water pumping and treatment system composed of appropriate technologies and powered by solar photovoltaic energy, capable of covering the community's water necessities, was calculated. To do so, operation characteristics of the water desalination and disinfection processes and of the independently powered pumping system were set. Next, the number of solar panels for the two PV systems, the capacity of the batteries (if applicable), and the size of the groundwater, desalinated water and disinfected water tanks were selected. Then, the behavior of the complete system was modelled under three different radiation conditions. The set quantity of solar panels and other elements was changed until the water needs of Campo Loro were met under the established conditions for each radiation data set. In these iterations, increasing the volume of the water tanks was preferred over increasing the amount of batteries or the number of solar panels.

It was found that the optimal system was composed by 52 solar panels, 3 water tanks of 65 m^3, 10 m^3, and 10 m^3, a groundwater pump, an EDR unit and an EWD unit. It is capable of ensuring availability of drinking-water for Campo Loro 99,9% of the times in a modelled span of 9 years. With capital and operating costs for 20 years of operation amounting to approximately 47,000 €, it desalinates 75,000 m^3 of water, resulting in a water cost of 0.64 €/ m^3. It must be noted that only the main elements of the system were considered when estimating the costs of the system. In future extensions of this study other components of the system such as cables or pipes, that represent small costs overall for the system, will have to be considered. Thus, the water costs may change slightly.

Other options for supplying the system were also studied for comparison. The water cost associated to supplying the water pumping and treatment system with the Paraguayan electricity grid and with a diesel generator were calculated. The obtained results were 0.73 €/m^3 and 0.91 €/m^3 respectively, which are higher than the associated costs to the designed system in this work. Additionally, the designed system would not have associated CO_2 emissions or depend on the installation of national electrical infrastructure, which favors choosing it over the other two presented options.

The continuation of this master's thesis will begin with a visit to the community as soon as possible, so that detailed information can be gathered, and the system can be re-designed. Other activities, systems, or technologies may be included in the Goodwill Action in Campo Loro during this stage, and it also has the possibility of evolving into the full development of a Sustainable Community in Campo Loro under the Sustainable Community Project of CLRLA-UNESCO.

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Annex

Annex A: Calculating irradiance on a 20° angle tilted panel

To calculate the irradiance on a tilted surface the following equations are needed:

$$G_T = G_b R_b + G_d \left(\frac{1 + cos\beta}{2}\right) + (G_b + G_d)\, \rho_g \left(\frac{1 - cos\beta}{2}\right) \qquad \textit{Eq. 8}$$

Where:

$$R_b = \frac{cos(\lambda - \delta + \beta)}{cos(\lambda - \delta)} \qquad \textit{Eq. 9}$$

(only valid for the Southern Hemisphere)

And:

$$\delta = 23.45\, sin\left(360\left(\frac{284 + d}{365}\right)\right) \qquad \textit{Eq. 10}$$

In these equations, G_b is the direct irradiance, G_d is the diffuse irradiance, β is the surface angle (in our case, 20°), ρ_g is the surface albedo (which is estimated as 0.15 for work[5]), λ is the latitude of the location, δ the declination, and d is the Julian day.

Annex B: EDR model by Wright et al.

It is composed of the five main equations 11 – 15 [65].

First, an EDR stack can be modeled as an analogous DC circuit:

$$E_{total} = E_{el} + NE_{mem} + Ni(R_d^b + R_c^b + R^{BL} + R^{AEM} + R^{CEM}) \qquad \textit{Eq. 11}$$

where N is the number of cell pairs in the stack, and i is the current density (A/m^2). The area resistances R_d^b, R_c^b, R^{BL}, R^{AEM} and R^{CEM} ($\Omega\ m^2$) are associated with the bulk diluate and concentrate streams, the concentration boundary layers, and the exchange membranes (anion exchange membranes (AEM), cation exchange membranes (CEM)), respectively. Finally, E_{el} is the electrode potential difference and E_{mem} is the potential across each membrane-pair (V).

Then, mass balance equations of the diluate and concentrate tanks are necessary to know their rate of concentration change. For the diluate tank, the mass balance is:

$$\frac{dC_{d,0}^b}{dt} = \frac{1}{V_d^{tank}}\left[Q_d\left(C_d^b - C_{d,0}^b\right)\right] \qquad \textit{Eq. 12}$$

And for the concentrate tank:

$$\frac{dC_{c,0}^b}{dt} = \frac{1}{V_c^{tank}}\left[Q_c\left(C_c^b - C_{c,0}^b\right)\right] \qquad \textit{Eq. 13}$$

[5] Based on the values given in [82].

Where C_d^b, C_c^b, $C_{d,0}^b$, and $C_{c,0}^b$ are the concentrations of the diluate and concentrate streams at the inlet and outlet of the ED stack, Q_d and $Q_c$are the flow rates of the diluate and concentrate streams, and V_d^{tank}tank, V_c^{tank}tank are the volumes of water in the dilute and concentration tanks, respectively.

Lastly, mass balance equations are also needed to know the concentration of the diluate and concentrate streams in the EDR stack throughout the desalination process. The mass balance for the diluate stream is:

$$\frac{dC_d^b}{dt} = \frac{1}{NV^{cell}}\left[Q_d\left(C_{d,0}^b - C_d^b\right) - \frac{N\phi I}{zF} - \frac{NAD^{AEM}(C_c^{AEM} - C_d^{AEM})}{l^{AEM}} - \frac{NAD^{CEM}(C_c^{CEM} - C_d^{CEM})}{l^{CEM}}\right] \quad \textit{Eq. 14}$$

And for the concentrate stream:

$$\frac{dC_c^b}{dt} = \frac{1}{NV^{cell}}\left[Q_c\left(C_{c,0}^b - C_c^b\right) + \frac{N\phi I_y}{zF} - \frac{NAD^{AEM}(C_c^{AEM} - C_d^{AEM})}{l^{AEM}} - \frac{NAD^{CEM}(C_c^{CEM} - C_d^{CEM})}{l^{CEM}}\right] \quad \textit{Eq. 15}$$

Where A is the area of one cell, ϕ is the current leakage factor, I is the current in the discretized segment, z is the ion charge number, F is Faraday's constant, l^{AEM} and l^{CEM} are the thicknesses of the anion and cation exchange membranes, $D^{AEM}$and D^{CEM} are the diffusion coefficients of the solute in the AEMs and CEMs, and C_c^{AEM}, C_d^{AEM}, C_c^{CEM} and C_d^{CEM} are the concentrations of the diluate and concentrate streams at the interface with adjacent AEMs or CEMs.

Annex C: Complete budget description

Capital costs associated with Design III.B

Item	Units	Price	Total
PV systems			
ERA polycrystalline 340 W 24 V solar panels			
Water treatment system	48	136.25 €	6,540 €
Pumping system	4	136.25 €	545 €
Victron Phoenix C 24 V 1600 VA Inverter	1	793.65 €	793.65 €
EDR[6]			
Membrane pairs	80	135 €	10,800 €
Electrodes	2	1800 €	3,600 €
Grundfos multicell CM3-3 1x220 pump (for concentrate, diluate and electrode solution pumping)	3	193.13 €	579.39 €
Electrochemical disinfection unit	1	200 €	200 €
Grundfos multicell CM3-3 1x220 pump (for filling/emptying tanks)	2	193.13 €	386.26 €
IDEAL SJ8 0.75 CV submersible pump	1	332.51 €	332.51 €
Tanks (units in m^3)			
Desalinated water tank	65	100 €/m^3	6,500 €
Disinfected water tank	10	100 €/m^3	1,000 €
Groundwater tank	10	100 €/m^3	1,000 €
EDR – Concentrate tank	0.16	100 €/m^3	16 €
EDR – Diluate tank	0.65	100 €/m^3	65 €

TOTAL	**32,357.81 €**

Operating costs associated with Design III.B for 20 years of operation

Item	Units	Price	Total
EDR			
Membrane pairs (one replacement)	80	135 €	10,800 €
Electrodes (one replacement)	2	1800 €	3,600 €

TOTAL	**14,400 €**

[6] Prices for the membrane pairs and electrodes have been taken from [68].

Annex D: Modelled operation of design III.B

Loss of load throughout 2010 – 2018 = 0.09%