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Energy and Water Nexus: off-grid desalination

A critical review and a multi-criteria approach to alternatives selection

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Quand tu veux construire un bateau, ne commence pas par rassembler du bois,
couper des planches et distribuer du travail,
mais reveille au sein des hommes le desir de la mer grande et large.

If you want to build a ship, don't drum up the men to gather wood,
divide the work and give orders.
Instead, teach them to yearn for the vast and endless sea.

Antoine de Saint Exupéry

Contents

List of Figures

List of Tables

Abstract

Access to clean water has risen for importance at the top of policy makers agenda, due to the growth of world population and the climate changes.

Several populated regions facing water scarcity are located in coastal regions with access to seawater, or in arid inland areas with access to brackish groundwater. Desalination would be a logical solution for these regions, but it is an energy-intensive process that usually relies on fossil fuels. Conventional desalination systems powered by fossil fuels produce environmental pollution and emission of greenhouse gases and they strongly depend on the unpredictable fluctuations of the oil and gas market prices.

Certain developing countries experience energy scarcity as well as water scarcity, in particular in rural areas: hence, the challenge is to develop innovative and sustainable water-energy solutions, capable to provide with freshwater rural areas with no access to the electric grid.

The present study starts relying on a critical literature review on desalination solution strictly focused on technologies appropriate for small-scale off-grid desalination. From the critical review emerges that there is no best method of desalination: the selection of a solution depends on a careful study of the context, since local circumstances may play a significant role in determining the most appropriate process for a rural area.

Hence, a multi-criteria decision method based on the Analytic Hierarchy Process, able to support non-technical decision-makers, is defined through the definition of the hierarchy of the problem and of a set of indicators capable to evaluate the full sustainability of the technical solution. The model is then tested on a case study.

Once the most appropriate technology is identified, it is necessary to proceed with the detailed design of the desalination system. The present study eventually shows the challenges of this phase, describing the pre-feasibility study and the design of a renewable energy system (RES) intended to power a desalination laboratory at the American University in Cairo (AUC, Egypt). The pre-feasibility study includes the detailed analysis of the energy requirements of the laboratory together with an accurate assessment of the renewable energy potential of the AUC campus. Several scenarios based on this assessment study are then developed, in order to identify the most appropriate RES and to proceed with the detail design of the system.

Keywords: desalination, renewable energy system, sustainability, Analytic Hierarchy Process, Egypt

Estratto in lingua italiana

Il problema dell'accesso all'acqua è ai primi posti nell'agenda politica internazionale, a causa dell'aumento della popolazione mondiale e dei cambiamenti climatici. La desalinizzazione è quel processo che trasforma acqua ad alto contenuto salino in acqua potabile, e può essere parte integrante della soluzione a questo problema.

La sete di energia dell'acqua

Secondo i dati delle Nazioni Unite 2 miliardi di persone non hanno un accesso sicuro all'acqua potabile, mentre il numero di persone il cui bisogno d'acqua non è soddisfatto pienamente si stima essere pari a 3.5 miliardi. A causa dei cambiamenti climatici e dell'aumento di popolazione questi numeri sono destinati a salire: in particolare si prevede che la domanda d'acqua crescerà del 55% entro il 2050.

Il problema dell'energia è altrettanto grave: si stima infatti che 1.3 miliardi di persone non abbiano ancora accesso alla rete elettrica e che il 95% di esse siano concentrate nelle aree rurali dei paesi africani.

Acqua ed energia sono due temi fortemente interconnessi ed interdipendenti: l'acqua è richiesta per produrre, trasportare e utilizzare le varie forme di energia, mentre l'energia è necessaria per l'estrazione, la purificazione e il trasporto dell'acqua. Soluzioni appropriate ad uno dei due temi potrebbero avere facilmente conseguenze sull'altro: a questo legame si dà il nome di *water and energy nexus*.

Il problema dell'acqua e dell'energia è ancora più evidente nei contesti rurali, dove la mancanza d'acqua è spesso accompagnata dalla mancanza di accesso alla rete elettrica e a combustibili fossili tradizionali. È quindi necessario impiegare soluzioni innovative, che risolvano allo stesso momento il problema dell'acqua e dell'energia in maniera sostenibile, cioè soddisfacendo i bisogni del presente senza compromettere quelli delle generazioni future. In particolare questo concetto si fonda su tre dimensioni fondamentali:

- Sostenibilità economica: è la dimensione che misura la capacità di una soluzione di auto sostenersi economicamente nel tempo
- Sostenibilità ambientale: è la dimensione che considera tutti gli effetti che la soluzione ha sull'ambiente

- Sostenibilità sociale: è la dimensione che tiene conto degli effetti che una soluzione ha su tutti gli stakeholder, con particolare riferimento alle comunità locali coinvolte

Fornire energia alle aree rurali vuole dire affrontare problematiche diverse da quelle dei contesti più tradizionali. In particolare è necessario scegliere tecnologie indipendenti, affidabili, di piccola taglia e di facile manutenzione. Tecnologie con queste caratteriste, e quindi adatte ai contesti rurali sono:

- Generatori diesel, già ampliamente utilizzati nelle aree rurali.
- Tecnologie alimentate da energia solare, in particolare pannelli fotovoltaici e collettori solari.
- Mini e micro turbine eoliche, sfruttanti l'energia del vento.
- Tecnologie che utilizzano la biomassa, ovvero piccoli impianti di gassificazione e digestori anaerobici.

Analisi critica delle tecnologie di desalinizzazione adatte alle aree rurali

Molto spesso le regioni affette da mancanza di acqua potabile hanno accesso ad acqua marina o salmastra, a seconda che siano situate rispettivamente sulle coste o nell'entroterra: la desalinizzazione sarebbe quindi una soluzione naturale al problema dell'acqua in queste regioni; tuttavia essa è un processo che richiede molta energia.

Le tecnologie di desalinizzazione convenzionali spesso suppliscono a questo bisogno di energia con l'utilizzo di combustibili fossili, producendo quindi un forte impatto ambientale ed emissioni di gas serra. Inoltre il costo dell'acqua prodotta da questi impianti è fortemente legato alle imprevedibili fluttuazioni del mercato del petrolio e del gas e non può essere sostenuto dai paesi in via di sviluppo, specialmente nelle aree rurali dove il costo per l'approvvigionamento dei combustibili è spesso proibitivo. È necessario dunque identificare le tecnologie di desalinizzazione adatte ad applicazioni rurali studiando i possibili metodi per alimentarle.

Dalla analisi di 109 pubblicazioni scientifiche su questo tema, sono state selezionate e studiate cinque tecnologie. Inoltre per ogni tecnologia è stato identificato un set di parametri tecnico-economici significativi, di modo da poterle comparare e sottolinearne pregi e difetti. Le tecnologie selezionate si possono suddividere in termiche e a membrana, a seconda del processo sfruttato, e sono:

Alambicchi solari Tecnologia termica molto semplice e di facile realizzazione, gli alambicchi solari riproducono sostanzialmente delle micro serre. Il principio di funzionamento si basa sulla evaporazione dell'acqua salmastra grazie alla radiazione solare. La facilità di costruzione utilizzando manodopera e materiali locali rende gli alambicchi solari soluzioni interessanti per la produzione di piccole quantità di acqua potabile.

Ciclo di umidificazione e de-umidificazione Questa tecnologia riproduce il ciclo naturale dell'acqua: inizialmente l'acqua salmastra evapora, diventando umidità contenuta in un flusso d'aria (fase di evaporazione); quindi l'umidità dell'aria si condensa diventando acqua potabile (fase di condensazione). Il processo è alimentato in massima parte da collettori solari.

Distillazione a membrana Questa tecnologia termica sfrutta una membrana permeabile solo al vapore acqueo, che è frapposta a due flussi d'acqua, uno freddo ed uno caldo. Le molecole di vapore presenti nel flusso caldo passano la membrana e condensano all'esterno, diventando così acqua potabile. L'acqua viene scaldata da collettori solari.

Osmosi inversa Se si frappone una membrana semipermeabile a due fluidi a concentrazione diversa, si crea una differenza di pressione grazie alla quale il solvente puro migra naturalmente dalla soluzione meno concentrata a quella più concentrata; questo fenomeno prende il nome di osmosi, e la pressione si chiama pressione osmotica. Se si applica una pressione esterna maggiore della pressione osmotica, il flusso si inverte. Questo processo è chiamato osmosi inversa, e viene largamente utilizzato per la desalinizzazione; esso è classificato come processo a membrana. La pressione atta a vincere quella osmotica è garantita da una pompa, alimentata elettricamente. Nelle aree rurali questi sistemi vengono ampliamente utilizzati accoppiati a mini reti off-grid, in grado di fornire l'energia elettrica richiesta dalle pompe; tali mini reti possono essere composte da pannelli fotovoltaici, mini e micro turbine eoliche, impianti a biogas e generatori diesel.

Elettrodialisi L'elettrodialisi è una tecnologia a membrana in cui, applicata una differenza di potenziale, si ottiene la separazione dei sali disciolti come ioni positivi e negativi dall'acqua salata da purificare, grazie all'impiego alternato di membrane cationiche e anioniche poste all'interno dell'unità. Nelle aree rurali, la corrente continua richiesta dal processo può essere convenientemente fornita da panelli fotovoltaici e batterie. Il processo è molto competitivo per basse salinità dell'acqua da depurare.

Dal confronto fra tutte queste tecnologie emerge che è impossibile ordinarle in una classifica assoluta e sceglierne una che sia la migliore per tutti i contesti: infatti non solo i parametri tecnico-economici dipendono fortemente dal contesto, ma anche l'impatto sociale ed ambientale della desalinizzazione cambia a seconda della tecnologia impiegata. Un profondo studio del contesto locale, la conoscenza degli stakeholder coinvolti e uno studio di fattibilità tecnica-economica sono necessari al fine di scegliere correttamente la tecnologia di desalinizzazione più appropriata per una specifica area rurale.

Un approccio multicriteriale alla desalinizzazione rurale

A causa dei pregi e difetti di ogni tecnologia di desalinizzazione, della diversità di obiettivi e dei vincoli che dovrebbero essere soddisfatti contemporaneamente, la selezione della migliore tecnologia per uno specifico contesto risulta essere molto complessa. Inoltre è difficile trovare dati affidabili e precisi riguardanti le aree rurali, rendendo ancora più complesso il problema.

Al fine di aiutare *decision-makers* che volessero impiegare una tecnologia di desalinizzazione in un contesto rurale, in particolare quelli senza background tecnico, nella complessa azione di scelta della tecnologia più appropriata, è stato formulato un metodo decisionale, ovvero una procedura che permetta di analizzare un problema secondo un set di regole, in modo da poter giudicare le possibili soluzioni e scegliere la migliore fra di esse in base alle stesse regole prima definite.

Considerando la natura del problema preso in considerazione, l'*Analytic Hierarchy Process* (AHP) è stato scelto come metodo decisionale più adatto. Esso infatti struttura approfonditamente il problema, considerando sia indicatori qualitativi che quantitativi e basandosi sui giudizi di tutti gli attori coinvolti nella decisione. Questo metodo presuppone la scomposizione del problema in sotto-problemi, creando così una precisa gerarchia, e ne determina i pesi tramite comparazioni a coppie, effettuate dagli stessi fruitori del metodo. L'AHP si struttura nelle seguenti fasi:

Scomposizione gerarchica del problema In questa fase si definiscono l'obiettivo, i criteri e gli eventuali sotto criteri che devono essere soddisfatti per raggiungere tale obiettivo e si ipotizzano le possibili soluzioni al problema, ovvero le alternative tra le quali è necessario scegliere. Il risultato è la scomposizione del problema in una gerarchia.

Assegnazione di un punteggio a ogni alternativa sulla base di un confronto a coppie Per stabilire le priorità tra i vari elementi di ciascun livello della gerarchia si utilizzano confronti a coppie: gli elementi di un livello della gerarchia vengono confrontati a coppie, rispetto ogni elemento posto al livello superiore. Il risultato è la creazione per ogni criterio di una matrice di comparazione, i cui elementi sono coefficienti, detti di dominanza, che rappresentano l'importanza di un elemento rispetto all'altro in base al criterio considerato.

Aggregazione dei dati Da ogni matrice di comparazione è calcolabile un vettore, i cui elementi rappresentano la scala di importanza di tutte le alternative rispetto ad un criterio. La composizione gerarchica di tutti i vettori ha come risultato l'identificazione di un vettore globale di priorità, che rappresenta la scala di importanza di tutte le alternative rispetto all'obiettivo finale. Grazie a questo vettore si individua quale è l'alternativa migliore.

Nell'applicazione del metodo gli elementi fondamentali sono la scelta delle alternative e dei criteri. Nel caso della desalinizzazione le alternative sono da scegliersi tra le tecnologie prima descritte, in base ad un criterio di fattibilità tecnica.

I criteri sono invece basati sulle tre dimensioni della sostenibilità: la bontà della soluzione è infatti misurata in egual maniera secondo quanto essa è in grado di valorizzare le dimensioni economica, ambientale e sociale. Le tre dimensioni della sostenibilità vengono quindi usate come criteri principali. La valutazione di questi criteri principali passa attraverso l'analisi di sotto criteri, i quali sono a loro volta valutati da indicatori. Di seguito si riporta la lista dei criteri e degli indicatori, individuati grazie all'analisi critica delle tecnologie di desalinizzazione.

Dimensione economica Essa è valutata attraverso i sotto criteri di fattibilità, prestazione e sostenibilità economica. Gli indicatori scelti sono:

- Costo di produzione dell'acqua (quantitativo): rappresenta il costo di produzione di un metro cubo di acqua prodotto dal sistema
- Costo di investimento specifico (quantitativo): esprime il costo dell'investimento iniziale per ogni metro cubo di capacità giornaliera installata
- Modello di business (qualitativo): rappresenta quanto la tecnologia si adatta al modello di business reputato più consono a uno specifico contesto

Dimensione ambientale I sotto criteri che fanno a capo a questa dimensione sono l'inquinamento dell'atmosfera locale, l'utilizzo del suolo ed altri impatti ambientali. Gli indicatori atti a valutare questi criteri sono:

- Occupazione specifica di suolo (quantitativo): misura la spazio richiesto dall'impianto per ogni metro cubo di capacità giornaliera installata
- Inquinamento locale dell'aria (quantitativo): misura la quantità di particolato, SO_x ed NO_x prodotti ed emessi dall'impianto
- Impatti ambientali minori (qualitativo): tiene conto degli impatti ambientali che sono solitamente di poco rilievo, come l'impatto visivo, il rumore e il cattivo odore
- Strategia di smaltimento dell'acqua salmastra (qualitativo): tutte le tecnologie di desalinizzazione producono come scarto di produzione una certa quantità di acqua ad alto contenuto salino, che deve essere appropriatamente trattata, di modo che non arrechi danno all'ambiente; ogni impianto di desalinizzazione deve prevedere una destinazione di questo flusso di scarto. Questo indicatore misura la qualità della strategia di smaltimento dell'acqua salmastra proposta insieme alla tecnologia

Dimensione sociale I diversi sotto criteri che la compongono tengono conto di tutti quegli aspetti tecnologici che hanno un impatto sulla società locale. I suoi sotto criteri sono l'impatto diretto sul lavoro, l'accettabilità sociale e la capacità di fornire servizi alla comunità. Gli indicatori scelti sono:

- Impatto sul lavoro locale (qualitativo): indica quanto lavoro locale le attività di l'installazione, manutenzione e gestione dell'impianto possono creare

- Miglioramento di altri servizi (qualitativo): valuta se la tecnologia è in grado di erogare, oltre alla produzione di acqua potabile, altri servizi alla comunità, come ad esempio la fornitura di elettricità
- Modularità tecnologica (qualitativo): definisce quanto la tecnologia analizzata è in grado di adattarsi ad una possibile domanda crescente di acqua potabile
- Livello di accettabilità sociale (qualitativo): stima quanto la soluzione proposta potrebbe essere accettata o meno dalla popolazione locale. È un indicatore indispensabile ma molto complesso, che richiede un grande sforzo di analisi del contesto locale

Il modello è stato quindi testato su un caso reale, in modo da studiarne il comportamento e la correttezza nella pratica. Questo caso reale consiste in un impianto di desalinizzazione basato sull'osmosi inversa, alimentato con pannelli fotovoltaici. Il sistema è stato costruito in un villaggio rurale situato in Marocco, senza accesso alla rete e affetto da scarsità d'acqua. I progettisti appartengono all'*Istituto Tecnòlogico de Canaria* (ITC), istituzione con esperienza nel campo dei sistemi rurali per la produzione di acqua potabile, e l'impianto è stato finanziato dal progetto *ADIRA*, il cui scopo era promuovere lo studio e l'implementazione di impianti di desalinizzazione decentralizzati.

In particolare si è voluto comparare il sistema effettivamente installato con altre possibilità adatte a quel contesto e si è voluto indagare se la scelta compiuta dall'ITC sia stata veramente la migliore. Si sono quindi supposte due alternative: la prima basata sugli alambicchi solari, e la seconda sul ciclo di umidificazione e de-umidificazione, i cui dati e materiale tecnico sono stati presi dall'archivio del progetto *ADIRA*; le matrici di comparazione sono state compilate in base ai dati delle tecnologie e alle informazioni riportare sul contesto locale.

Il risultato finale dimostra che il modello individua la stessa soluzione scelta dall'ITC: questo risultato è considerato positivo, poiché il modello si allinea ad una decisione ritenuta giusta, in quanto concepita da un team di esperti del settore. Tuttavia si è notato come i pesi assegnati a ogni indicatore rispetto ai criteri principali (sostenibilità economica, ambientale e sociale), possano cambiare moltissimo a seconda del contesto locale, e siano quindi determinanti al fine dell'individuazione della soluzione ottima.

L'applicazione ad progetto ancora da implementare e in diversi contesti è necessaria al fine di validare in via definitiva il modello.

Sistemi ad energia rinnovabile per la desalinizzazione: il caso di studio all'AUC

Supportati dal modello decisionale sviluppato in questa tesi è possibile scegliere il sistema di desalinizzazione più appropriato ad uno specifico contesto rurale; si pone quindi il problema della progettazione di dettaglio del sistema selezionato.

Come si è già spiegato, gli impianti ad osmosi inversa possono essere alimentati da differenti sistemi per la produzione di energia elettrica. La selezione del migliore fra essi dipende fortemente dal contesto locale. A titolo di esempio la tesi riporta la procedura di selezione del migliore sistema a energia rinnovabile [1] (*Renewable Energy System*, RES) atto ad alimentare un laboratorio incentrato sulle tecnologie di desalinizzazione a membrana, in costruzione presso l'American University in Cairo. La procedura di selezione ha richiesto una valutazione dettagliata dei carichi del laboratorio e del potenziale rinnovabile del campus dell'università. In conclusione la tesi riporta la progettazione di dettaglio dell'impianto selezionato, svolta direttamente sul campo.

La selezione del RES dipende in massima parte dalle condizioni locali e dalla tipologia di richiesta elettrica dell'impianto. I passi seguiti per la selezione del RES sono:

Valutazione del carico La struttura analizzata presenta sia una richiesta di energia elettrica - dovuta principalmente al consumo delle pompe che alimentano i sistemi di desalinizzazione - che una richiesta di energia termica derivante dalla necessità di condizionamento dell'aria dell'edificio stesso. Si deve notare infatti che le membrane presenti all'interno del laboratorio devono lavorare in un intervallo di temperatura ben definito, garantito da pompe di calore che servono l'edificio. Il consumo elettrico è stato calcolato tramite le specifiche tecniche dei dispositivi installati nel laboratorio, mentre quello termico tramite una simulazione termica dell'edificio sviluppata con il software *DesignBuilder*. Periodici incontri con i fornitori dell'impianto si sono resi necessari per accompagnare il processo di valutazione dei carichi, dal momento che il laboratorio non era ancora entrato in funzione al momento dello studio. Il consumo elettrico e quello termico, convertito in elettrico tramite il coefficiente di prestazione delle pompe di calore, sono stati sommati per ottenere il carico elettrico totale richiesto dal laboratorio.

Valutazione del potenziale energetico del campus Si è studiato il potenziale solare, eolico e biomassico del campus della AUC dove è costruito il laboratorio. Data la mancanza di dati affidabili su energia solare ed eolica nel contesto egiziano, si è fatto uso della letteratura e di database climatici (*Autodesk Climate Server*), al fine di individuare le caratteristiche della radiazione solare e della ventosità locale durante l'anno. La biomassa è stata studiata avvalendosi degli studi compiuti dalla AUC sulla produzione interna di rifiuti solidi e di studi specifici di letteratura.

Simulazione dei possibili sistemi energetici Avendo come input la valutazione del carico elettrico e del potenziale rinnovabile del campus, è stato impiegato *HOMER Energy*[2] per simulare tutti i possibili tipi di impianti ed individuare pregi e difetti di ogni soluzione tecnica.

Tenendo conto dei vincoli dati nel contesto della AUC, è emerso che un sistema rinnovabile basato solo su pannelli fotovoltaici fosse il migliore. La tesi presenta quindi la progettazione di dettaglio dell'impianto fotovoltaico, che ha riguardato in particolare la possibilità di integrare

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[1] si noti che per motivi di impatto ambientale l'utilizzo di un generatore diesel è stato da subito escluso

[2] Software di simulazione energetica focalizzato su impianti rinnovabili off-grid

un accumulo elettrico, per poter impiegare il sistema in modalità off-grid, e la disposizione dei pannelli fotovoltaici nello spazio disponibile. Da ultimo si riporta la descrizione della procedura di selezione della migliore offerta tecnico-commerciale, proposta dai fornitori di sistemi fotovoltaici in Egitto.

Conclusioni

Il problema della mancanza d'acqua è esacerbato nelle aree rurali dalla contemporanea mancanza di forme di energia moderne, quali combustibili fossili ed elettricità. Affrontare il problema dell'acqua in queste aree significa innanzitutto affrontare il problema dell'energia ad esso connesso. La tesi offre il proprio contributo allo studio del water and energy nexus concentrandosi sulle soluzioni tecniche adatte alla desalinizzazione rurale, sottolineando innanzitutto come esse debbano essere scelte ed implementate impegnandosi a perseguire una piena sostenibilità. Nel presente lavoro sono stati quindi affrontati principalmente tre passi:

Analisi critica della letteratura Cinque tecnologie di desalinizzazione sono state identificate come appropriate per applicazioni rurali off-grid e ne sono state analizzate le principali caratteristiche tecnico-economiche, con particolare rilievo al consumo energetico. Sono stati messi in luce vantaggi e svantaggi di ogni tecnologia, in modo da poterle comparare sotto ogni punto di vista. Dall'analisi critica della letteratura è emerso che alcuni sistemi analizzati sembrano particolarmente interessanti per il contesto rurale. Tuttavia è impossibile determinare una classifica assoluta fra le varie soluzioni, in quanto l'effettiva maggiore adeguatezza di una soluzione rispetto ad un'altra è estremamente dipendente dal contesto specifico. Risulta inoltre evidente la necessità di ulteriori ricerche e implementazione di progetti dimostrativi di queste soluzioni semplici, flessibili e di piccola scala, di modo da accrescere l'esperienza, la conoscenza e la fiducia nei loro confronti. Tali sforzi devono essere compiuti congiuntamente con tutti gli stakeholder interessati dai progetti di desalinizzazione rurale, in modo da sviluppare soluzioni pienamente sostenibili.

Metodo decisionale Risulta essere molto complicato identificare il sistema di desalinizzazione più appropriato per un dato contesto rurale, siccome le peculiarità di ogni soluzione sono fortemente legate al contesto stesso. Si è dunque deciso di sviluppare un metodo decisionale basato sull'Analytic Hierarchy Process, finalizzato a supportare i decision-makers in questa difficile scelta. Si è dunque definita una gerarchia appropriata al problema e un set di indicatori economici, ambientali e sociali, atti a valutare le possibili alternative tecnologiche. Sia la gerarchia che gli indicatori sono diretta conseguenza dello studio critico delle tecnologie di desalinizzazione. La formulazione di questo metodo decisionale ha permesso di capire ancora più profondamente quanto i sistemi di desalinizzazione da implementare in contesti rurali debbano essere valutati secondo le tre dimensioni della sostenibilità. Il metodo decisionale è stato testato su un impianto di desalinizzazione realmente costruito in un villaggio rurale dall'Istituto Tecnològico de Canaria (ITC). Il metodo decisionale ha selezionato il medesimo sistema di desalinizzazione implementato dagli esperti dell'ITC, e questo è considerato una prova dell'affidabilità del modello, pensato per supportare decision-makers non tecnici. Da questa applicazione si evince come il ruolo degli stakeholder locali sia essenziale, e come una profonda conoscenza del contesto sia necessaria al fine di impiegare in maniera appropriata il metodo.

Progettazione del RES Una volta che la tecnologia più adatta ad un contesto rurale è stata identificata, è necessario passare alla fase di progettazione di dettaglio del sistema. A titolo di esempio di una progettazione di questo tipo, la tesi ha presentato lo studio di fattibilità e l'effettiva progettazione sul campo di un RES atto ad alimentare un laboratorio incentrato sulle tecnologie di desalinizzazione, in costruzione presso l'American University in Cairo (AUC). Lo studio di fattibilità comprende lo studio della richiesta energetica del laboratorio e del potenziale di energia rinnovabile del campus; da esso sono emerse chiaramente le sfide implicate nel lavorare in un paese in via di sviluppo, come la mancanza e l'inaffidabilità dei dati disponibili. Il risultato dello studio di fattibilità è stata la selezione di un sistema rinnovabile basato sul fotovoltaico come sistema più opportuno per il contesto della AUC. Si è riportato da ultimo la procedura di progettazione effettivamente svolta sul campo, nella quale è risultata evidente, lavorando in un paese in via di sviluppo, la necessità di adattare il proprio metodo di lavoro alla cultura locale.

Possibili sviluppi della tesi si identificano in:

- Una analisi di mercato sulle tecnologie di desalinizzazione di piccola taglia, che potrebbe integrare lo studio della letteratura scientifica, fornendo così interessanti dati sul loro stato commerciale e sui costi effettivamente sostenuti nelle varie realtà del globo.
- L'applicazione del modello decisionale ad altri casi di studio, che potrebbe ulteriormente confermare la validità del metodo. Sarebbe soprattutto interessante studiare le sfide insite nella proposizione del metodo a decision-makers non tecnici.
- Lo studio del potenziale rinnovabile del campus AUC potrebbe essere confermato da misurazioni effettive.

Chapter 1

Water's thirst for energy

1.1 Water and energy scarcity

1.1.1 Worldwide overview

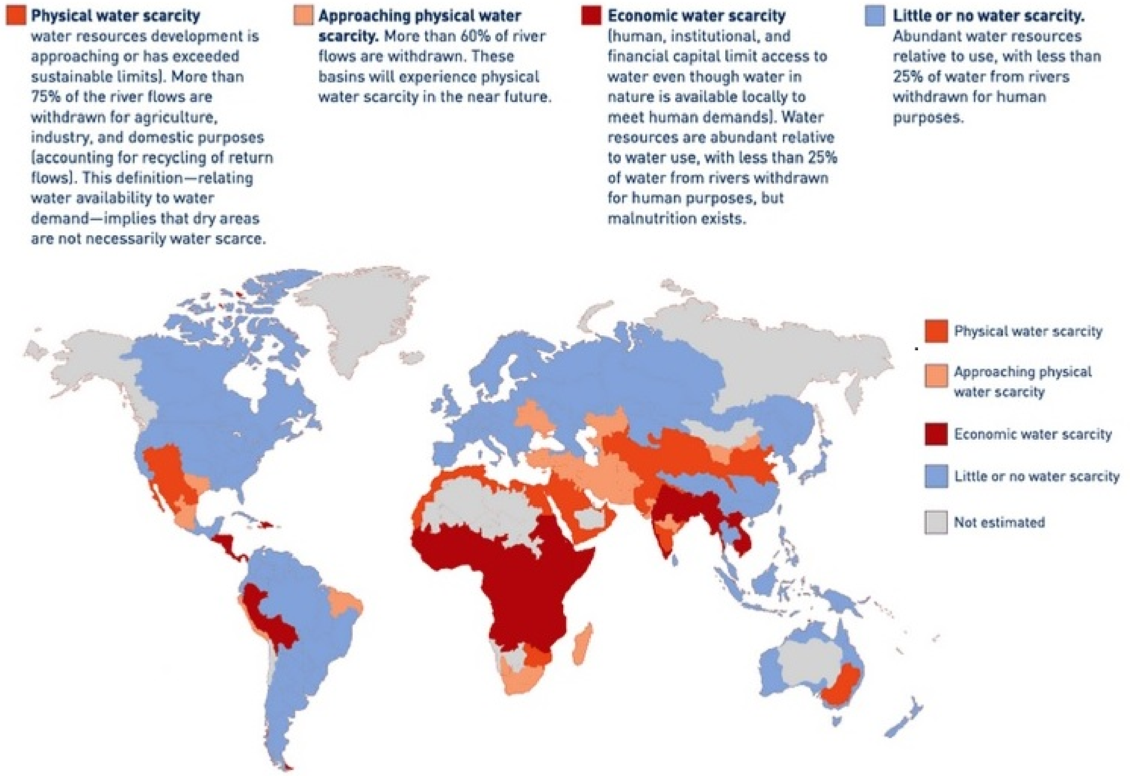
Fresh water and energy are critical resources to human well-being and sustainable socio-economic development and their roles is now widely recognized as essential in achieving progress towards every one of the Millennium Developing Goals [1]. In the recent past, rapid population growth and industrialization have placed pressing demands for both fresh water and energy especially in developing countries [2].

According to the World Health Organization (July 2014) [3], 748 million people rely on unimproved sources of water, thus risking to drink contaminated water. Among them, 173 million depend on surface water, such as rivers, lakes, ponds, etc. The High-level Panel on the Post-2015 Development Agenda has indicated that 2 billion people do not have access to safe water [4]. The number of people whose right to water is not satisfied is even greater, probably in the order of 3.5 billion [3]. Additionally, the availability of potable water resources is decreasing because of the worldwide climate change causing drought and desertification, the continuously increasing water demands, the population increase and the contamination of the existing water resources [1, 6]. Therefore, global water demand in terms of water withdrawals is projected to increase by some 55% by 2050.

Figure 1.1 shows regions that have limited water resources.

Supply of fresh water requires energy and, unfortunately, many countries in the world that lack freshwater sources are also deficient in energy sources. As a matter of fact, more than 1.3 billion people worldwide still lack access to electricity, with more than 95% of them located in sub-Saharan Africa and developing Asia, and 1 billion people are connected to a unreliable electric grid. In addition, roughly 2.6 billion people rely on the traditional use of biomass for cooking [1, 7, 8].

Figure 1.2 shows the total primary energy consumption by country. The similarity of the two maps pointing respectively energy- and water-short countries is manifest.



🟥 **Physical water scarcity** water resources development is approaching or has exceeded sustainable limits). More than 75% of the river flows are withdrawn for agriculture, industry, and domestic purposes (accounting for recycling of return flows). This definition—relating water availability to water demand—implies that dry areas are not necessarily water scarce.

🟧 **Approaching physical water scarcity.** More than 60% of river flows are withdrawn. These basins will experience physical water scarcity in the near future.

🟥 **Economic water scarcity** (human, institutional, and financial capital limit access to water even though water in nature is available locally to meet human demands). Water resources are abundant relative to water use, with less than 25% of water from rivers withdrawn for human purposes, but malnutrition exists.

🟦 **Little or no water scarcity.** Abundant water resources relative to use, with less than 25% of water from rivers withdrawn for human purposes.

Figure 1.1: Global physical and economic water scarcity [5]

1.1.2 Water and energy nexus

Water and energy are strongly interlinked: water is required to produce, transport and use all forms of energy somehow; and energy is required for the extraction, treatment and distribution of water, as well as its collection and treatment after use. Water and energy are also highly interdependent: standalone solutions that result to be appropriate for one single resource might lead to negative impacts on the other. These interlinkages and interdependencies, along with their negative and positive externalities, lie at the heart of what has become known as the *water and energy nexus* [1].

The interdependency of the two resources might have a huge impact on the local context. In the energy sector, for instance, thermal power plants require water for cooling, thus affecting the local environment of the source of surface water, whereas hydropower interferes with water flows and land use thus incubating the seeds of potential conflicts [8, 10].

The *Nile case* is one of the most representative examples of the social and political implications of the *water and energy nexus*. A colonial-era agreement had given downstream Egypt and Sudan rights to the Nile water without taking into account the nine other nations

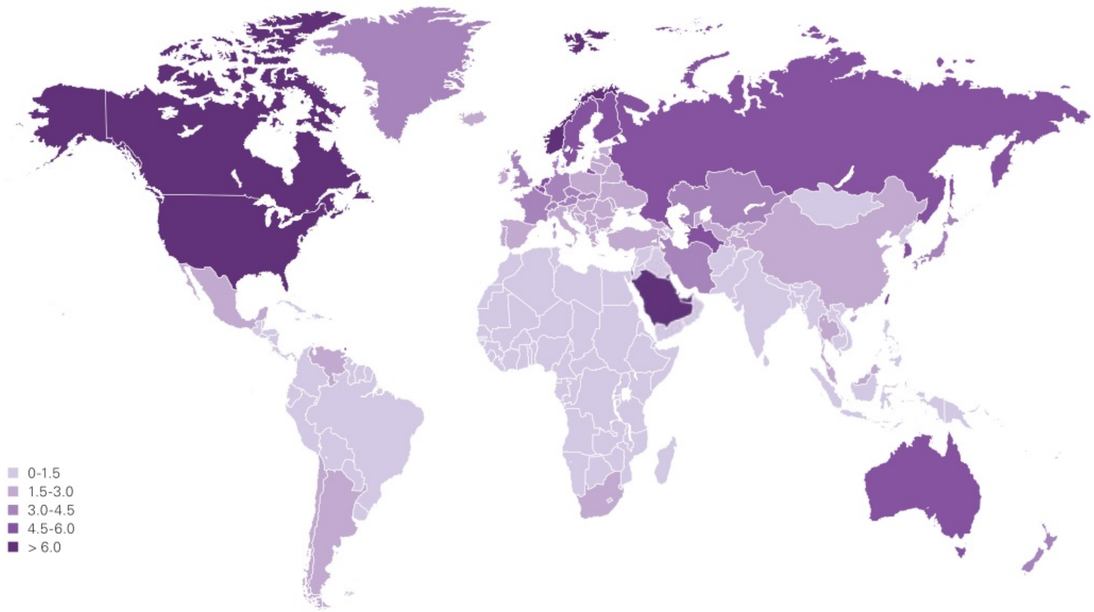


Figure 1.2: Total primary energy consumption 2013 - TPES ($toe/percapita$) [9]

along the 6,700-kilometre river [11, 12]. Actually, whereas the excluded countries have been agitating for a decade for a more equitable accord, the dependence of Egypt on freshwater withdrawal from the Nile is estimated at between 95% and 98% [11]. As observed by Benedito Braga, President of the World Water Council [13]:

> "Egypt is basically a country that depends on one source of water, the Nile, which is shared by eleven countries"

Nowadays, since Egypt regional hegemony is fading, other countries along the river are starting to unlock the Nile's potential for themselves. In 2011, Ethiopia - that is the source of almost 80% of the Nile water and it is facing energy scarcity - began building Africa's largest hydropower project, causing consternation in Cairo due to its potential to divert water from the river. Several important mass media have reported on July 2013 the statement of the then-president Mohamed Morsi [14, 15]:

> "If a single drop of the Nile is lost, our blood will be the alternative. We are not warmongers, but we will never allow anyone to threaten our security"

The Nile River is only one example of the huge social and political potential implications of water and energy scarcity. In order to prevent water wars, the need for an integrated planning approach is clear: finding feasible alternative water sources among the African countries is a major challenge that will stress societies economically, environmentally and politically [8, 10].

As it will be analyzed in chapter 2, among the available water sources, there are oceans and underground salty reservoirs: seawater and brackish water can be desalinated and supplied in large quantity. Unfortunately, this process requires a large amount of energy, and the overwhelming majority of the energy currently used for desalination is obtained from fossil fuels. As a matter of fact, water desalination is a typical example of technical solution that lies in the framework of the *water and energy nexus.*

1.1.3 Water and energy scarcity in rural areas

A rural area is defined as a region that is not urbanized and usually mostly devoted to agriculture; nevertheless, also arid regions are considered as rural areas. Thus, there is not a consensus about a clear definition of rural areas that suits all regions in the world and it actually varies from country to country according with national statistical offices [8]. However, it is possible to identify some common features of rural areas [16]:

- geographically isolated, with scarce or absent road network;
- scattered population;
- little or no access to modern and efficient sources of energy.

On the other hand, rural areas show huge differences in water availability. According to the local context, a very isolated small community might experience little or no water scarcity, whereas a larger and less-scattered settlement might face major problems due, for example, to the contamination of the groundwater or the pollution of the surface water.

One strong connection between energy and water is their social effect on the rural communities: in developing countries, women and girls bear most of the work burden associated with managing water and energy scarcity, fetching water for the 748 million people lacking access to improved sources of drinking water and collecting firewood for the 2.6 billion depending on traditional biomass for cooking [3, 7]. This phenomena adds to their time and work burdens and seriously compromises their educational and employment opportunities. Facing the water and energy scarcity means having a deep impact on the local social structure, giving the chance to women to get involved in more-professional jobs and to girls to have an education [1].

Another major interdependence between energy and water in rural areas is that the lack of energy exacerbates the water scarcity: the more an area suffers of water scarcity, the more it requires energy for addressing that issue. De facto, energy is required for drilling wells and extracting the water. It is also required for pumping the groundwater to the households and for irrigation; even more energy is required for water treatment and desalination processes, which are very energy-intensive.

Rural areas are not able to face the water issue, because of the lack of access to sources of modern energy. Therefore, addressing the water scarcity in rural areas means, even more than in urbanized water-scarce areas, addressing the related energy requirements.

The water and energy topics are also strongly linked to the food one. The connection between water, energy and food may be easily visible in the closed cycle represented in figure 1.3 that directly links the three elements of the nexus. These linkages can be simply explained as: "food needs crops and crops need to be irrigated". Water is globally used mainly for irrigation, and irrigation requires energy. When irrigation is insufficient, food security is then threatened [8].

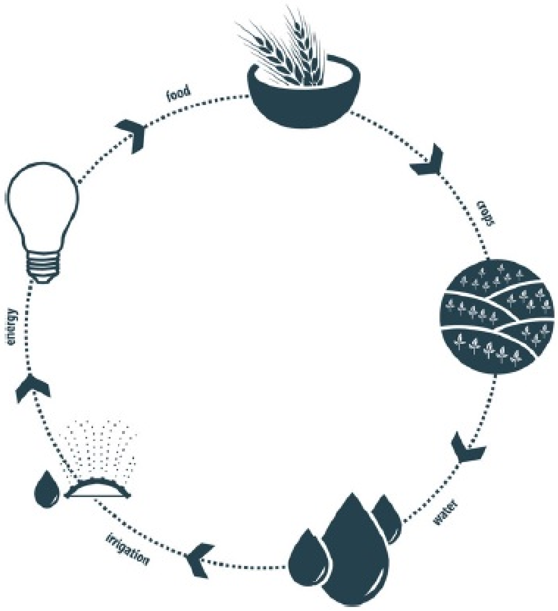


Figure 1.3: Water, Energy and Food nexus [8]

It is important also to underline another link between water and food, the so-called *land grabbing*. This term refers to the contentious issue of large-scale land acquisitions, i.e the buying or leasing of large pieces of land in developing countries, by domestic and transnational companies, governments and individuals. De facto, the real interest of the buyers relies in the water resource available in the acquired land bought in foreign countries, not in the land itself, hence the term *water grabbing* is often used. The *water grabbing* is another example of the direct link between water and food.

1.1.4 Addressing the water and energy nexus: the sustainability of the action

The *water and energy nexus* has to be dealt in a comprehensive manner, as it was already stated. Every action done on one of these two issues will eventually influence the other one and a deep knowledge of the links between them is then crucial. However, this knowledge is necessary but not sufficient to find out a proper solution: the actions addressing the *water and energy nexus* must be sustainable. This concept is strongly linked to the broader framework of the sustainable development, which can be defined according to Brundtland (1987) as [17]:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generation to meet their own needs"

Despite an on-going debate on the actual meaning of the sustainable development, this concept embraces the ideas of equity and fairness - i.e. the priority should be given to improving the conditions of the world's poorest countries - keeping also a long term perspective on the world's global challenges.

An action is defined sustainable if it addresses the three main dimensions of sustainability that are economic, environmental and social sustainability (see figure 1.4).

Figure 1.4: The three pillars of sustainability

In 2005, the General Assembly of the United Nations declared [18]:

> "We reaffirm that development is a central goal in itself and that sustainable development in its economic, social and environmental aspects constitutes a key element of the overarching framework of United Nations activities"

Basically, the goals of sustainable development are (UN, 2001 [19]):

> "To advance social and institutional development, to maintain ecological integrity and to ensure economic prosperity. Such goals echo basic human needs related to food, water, shelter, security, health, education, and good governance"

Therefore, a sustainable action has to consider and integrate all the effects that it might have on these three dimensions. It is important to understand the implications of the concept of sustainability while acting in rural areas, thus the three main dimensions of sustainability are now briefly described in accordance with the guidance provided by IAEA and United Nations regarding the themes that make up the three dimensions [19, 20, 21].

Economic sustainability Sustainable development requires a stable and healthy economy. To deliver a more sustainable economy, the use of various strategies for employing existing resources optimally is necessary in order to achieve a responsible and beneficial balance over the longer term.

Modern economies depend on a reliable and adequate energy supply, and developing countries need to secure this as a prerequisite for industrialization. All sectors of the economy - residential, commercial, transport, service and agriculture - demand modern energy services. Fresh water is also essential to support economic development, since it sustains domestic water supplies, food production, fisheries, industry, hydropower generation and navigation.

Every action aiming to address the *water and energy nexus* requires a starting investment and an expenditure for operation and maintenance costs. Hence, the economic sustainability requires a clear definition of the business model, i.e. the plan implemented by the actor to generate revenue and to recoup the incurred expenditures, in order to ensure the duration of the action.

Environmental sustainability The environmental sustainability considers the impact of an action over the environment. The production, distribution and use of energy as well as the extraction, treatment and distribution of water create pressures on the environment in the household, workplace and city, and at the national, regional and global levels. The environmental impacts can depend greatly on how energy is produced and used, and on how water is extracted and treated.

Usually, studying the environmental impact of an action means studying the impact of the action on the atmosphere, on the water ecosystem and on the land. For example, a diesel engine able to produce electricity in remote areas pollutes the local atmosphere, while a photovoltaic field might require a large land area. A desalination system providing fresh water to a local community discharges brine, i.e. very salty water, that might be harmful to the water and land environment.

In particular, the impact on the atmosphere can be studied separately at the global level and at the local level. At the global level, greenhouse gas emissions are at the heart of the debate on whether humankind is changing the climate for the worse, leading to global warming. On the other hand, air pollutants are of major concern at the local level, since they include sulfur oxides, nitrogen oxides, carbon monoxide and particulates (the last two being particularly important for indoor air pollution). These pollutants can damage human health, leading to respiratory problems, cancer, etc.

Therefore, actions addressing the nexus without consider their effects on the local environment might threaten present and future of the rural areas themselves.

Social sustainability The social sustainability is focused on the social impact of an action: addressing the *water and energy nexus* might have strong consequences on health and it can lead to a change in the local society, to an empowerment of local skills, to the creation or destruction of job opportunities.

Availability of water and energy has a direct impact on poverty, employment opportunities, education, demographic transition, indoor pollution and health, and it has gender- and age-related implications. In rich countries, energy for lighting, heating and cooking is available at the flip of a switch as well as water for drinking and washing is available at the turn of a tap. Energy and water are clean, safe, reliable and affordable. As already mentioned, in developing countries, several hours a day are required to collect wood and water and this task is usually done by women, who could be otherwise engaged in more productive activities. Moreover, high toll of disease and death through air pollution, fires and contaminated water results from burning wood without adequate equipment and ventilation and from drinking from unimproved sources of water.

Acting in the rural context implies a relationship with several different stakeholders. Among them, the families - who are the essential part of the rural area social fabric - are the actual target of the mentioned adversities and diseases thus they are also frequently the target of the action itself. The families interact with themselves sharing resources, information and assistance and establishing commercial relationships and forms of cooperation thus making up the so-called *local community.* A local institution in charge of the rural area is usually established by the national government. Although it is often far from the local context in itself, the government can be a donor and an important supporter of the action. In conclusion, the social sustainability has to consider the relation between the stakeholders and the concept of *acceptability,* i.e the overview of opinions related to the action by each stakeholder.

1.2 Energy technologies for rural areas: an overview

As it was stated in section 1.1, water extraction, treatment and distribution requires a large amount of energy, both thermal and electrical, which is not usually available in rural areas; thus, a particular attention to the energy systems appropriate for small-scale decentralized applications is needed. In particular, these systems must be extremely reliable, robust and cheap; the maintenance requirements and the complexity of the technologies have to be taken carefully into account, since it is often very difficult to make a proper upkeep of the equipment in rural areas.

The following paragraphs introduce the technologies that better match these requirements, thus being appropriate for the rural context.

1.2.1 Diesel generator

A diesel generator is the combination of a diesel engine with an electric generator (often an alternator) and it is commonly used to generate electrical energy. This technology is the most common and widespread one in rural areas, since it has lower initial capital cost than all the other competitive power technologies [8]. Moreover, the power generated by a diesel generator is flexible to work 24 hours thus meeting the energy needs of both domestic and income generating activities.

However, this conventional generation might implies very high operating costs in rural contexts, due to [22]:

- high diesel transporting cost to remote areas, where the existence of proper communication routes cannot be taken for granted;
- high maintenance costs, since regular maintenance, spare parts and routine checks are required by the presence of moving parts;
- high fuel consumption, since the efficiency of the generator deteriorates in course of time and the engine also usually operates at low efficiency due to the typical loads in remote areas that vary considerably during the day and night.

Moreover, a diesel generator has a lifetime of about 5-10 years (or an average value of 20,000 lifetime operating hours) and its life span will be shortened and the frequency of maintenance will be increased if it operates at less than about 30–40% of full load [23]. It is also not environmental friendly since it produces noise and a large amount of atmospheric pollutants.

1.2.2 Solar-driven technologies

The solar energy is the radiation that hits the earth surface and it is the most abundant of all the renewable energy sources. The main parameter by which it is possible to evaluate the potential of solar energy is the global horizontal radiation (W/m^2day), which measures the actual solar energy received by an horizontal surface. It can be employed for both thermal and electrical usages, through several different technologies. Among them, the most feasible for the rural context are the solar collectors and the photovoltaic panels, since they do not need skilled maintenance and they are appropriate for small-scale applications.

1.2.2.1 Solar collector

A solar collector is a device able to convert the solar radiation in thermal energy by mean of heating a fluid vector (usually water). It is a simple and easy-maintenance technology, which is composed by (see figure 1.5):

- Glass cover, transparent to the solar radiation but not to the thermal one. It also protects the pipes.

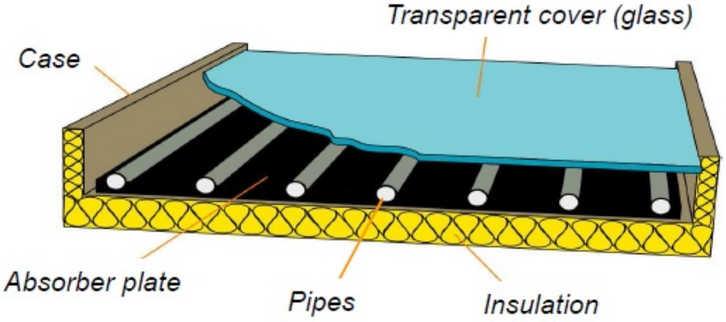


Figure 1.5: Schematic layout of a solar collector

- Absorber plate, where the solar radiation is collected and transformed in thermal energy.
- Pipes, where the vector fluid gets heated by the absorber plate.
- Case and insulation layer, that protects the pipes and avoid thermal losses towards the surrounding environment.

1.2.2.2 Solar photovoltaic

Solar photovoltaic (PV) generators are able to convert directly the solar radiation into electricity, through solar cells made of semiconductor-based materials. A solar panel is composed by a number of solar cells and it can typically provide from 80 to 250 peak Watt, according to its size and the chosen technology, while the conversion efficiency of each panel lies generally between 15 and 18 when silicon cells are used [24].

In order to achieve higher power production, it is possible to connect a number of solar panels, thus assembling a PV array able to provide the desired power output. Hence, the PV technology is modular and scalable, according to the load requirement. The output of a solar panel is a direct not-constant current (DC), since it depends on the solar incident radiation. Electrical load usually needs a source of constant alternating electrical current (AC), thus a PV system can power it only through the following devices (see figure 1.6) [8]:

- Battery bank, which is able to store the electrical output of the PV array and to feed the load when the solar radiation is scarce, thus ensuring a constant power supply to the load.
- Charge controller, which prevents the PV panels from over charging the batteries. It also avoids the discharge of the batteries below a certain level, in order to preserve the lifetime of the electrical storage.

- Inverter, that converts the DC current flowing from the PV system and from the batteries to AC current, assuring the voltage and the frequency required by the load.

The system needs also wires, cables and connection hardware. The PV technology is appropriate for small-scale rural applications, since it requires low maintenance and it is not characterized by economies of scale. Although it is a reliable and well-proved technology, problems of high temperatures and dust deposition have to be considered. A high panel temperature lowers the energy conversion efficiency and leads to the formation of hot spots that shorten its lifetime. The dust deposited on the panel's surface decrease the optical performance of the PV system and it is an important drawback, especially in rural areas where the operation and maintenance are difficult to be managed.

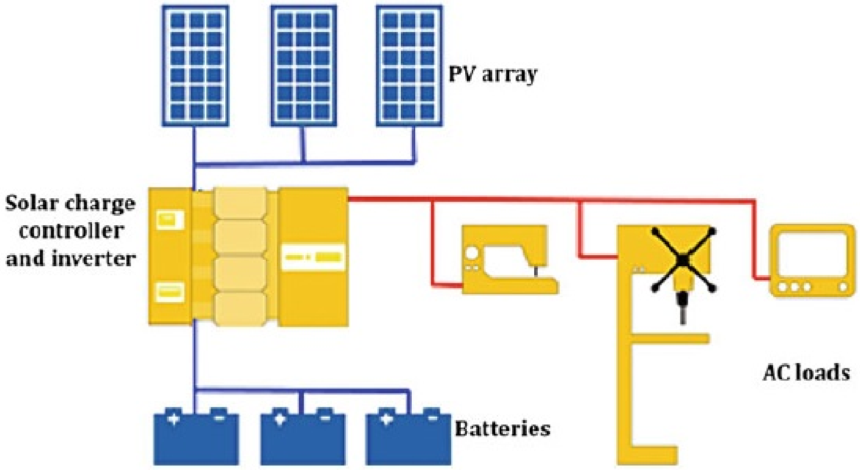


Figure 1.6: Schematic layout of an off-grid PV system [25]

1.2.3 Wind-driven technologies

Wind energy is a form of solar energy. The radiation coming from the sun hits the earth's atmosphere in a non-uniform way, thus different air masses get heated differently. The difference of temperature leads to a different densities, thus producing a movement between the air masses: wind is this continuous motion, and for its own nature is very site specific.

Wind resource is mainly characterized by the speed (m/s) and the blowing direction. A wind power generator (W/G), or wind turbine, transforms the kinetic energy of the wind into electrical energy, by means of a generator coupled with rotor blades. Wind turbines are appropriate for both small-scale (hundreds of Watts) and large-scale applications (up to some Megawatts), depending on the size of the turbine itself.

1.2.3.1 Micro and mini wind turbines

Rural areas do not require a large amount of energy and power capacity, thus small wind turbines - typically up to 50–100 kW - are used for stand-alone applications, with an average efficiency around 35% [24]. It should be noted that the minimum power capacity of a an energy system based on wind turbines is greater that the one of a system based on PV panels. There are several types of wind turbines and many efforts are being made in the design of new ones. However, since in rural context one of the main concern is the system reliability, it is important to employ mature technologies in order to enhance the sustainability of the applications. It cannot be also underestimated the chance to involve the local population in the production of artisan wind turbines, thus lowering the costs and increasing the local job opportunities and the ownership of the system by the communities [26, 27, 28, 29].

The wind turbines are divided in two main categories: horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT). HAWT technology, which implies that the rotor blades are perpendicular to the incoming airflow, is the most used in the rural context, since it is a well-proven technology and it can achieve higher efficiency than VAWT. Usually small HAWTs are self-orienting respect to the prevalent wind direction and the three-blade design is prevalent, since it reduces the vibration and the noise of the turbines. The most common configuration is the direct drive-permanent magnet rotor generator, since the main alternative requires a gearbox, thus increasing the required maintenance and the costs considerably. The hub is the upper part of the turbine, where the rotor blades are connected to the generator. Usually the hub's height for small wind turbines is 15 meters from the ground (see figure 1.7) [25].

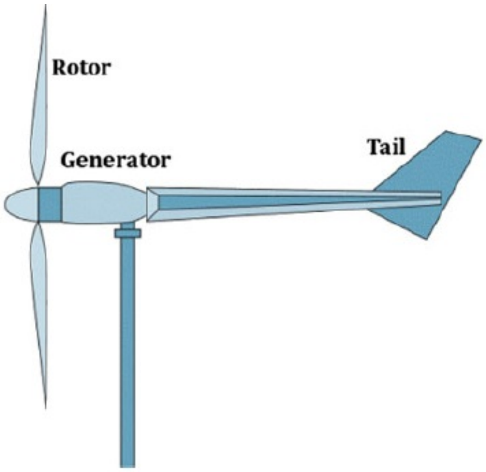


Figure 1.7: Composition of a small HAWT [25]

A small wind turbine produces AC current, with a frequency that varies according to the incoming wind speed. Hence, the power produced by a wind turbine needs to be converted

according to the request of the load, thus a bridge rectifier able to convert a discontinuous AC current in a constant DC one is needed. In order to give stability to the energy production, a common solution is to store the energy produced by the wind turbine in a battery bank and then to feed the electrical load through a proper inverter.
Usually small wind turbines feed rural mini-grids together with other power systems, such as a PV array or a diesel generator [8].

1.2.4 Biomass-driven technologies

The biomass resource comprehends a wide range of biodegradable organic products and waste from agriculture, forestry and industrial processes involving organic matter. The organic fraction of the urban waste and the wastewater from industrial and domestic usages are also accounted as biomass. The biomass resource is appropriate for both thermal and electrical energy production.

One main difference between biomass and other renewable resources is the complexity of the supply chain. The biomass can be produced for energy purpose, whether solar and wind can not; that production can be not sustainable, if it is not properly managed. Therefore, a deep attention on the social and environmental impact of the use of biomass is needed.

The traditional and most-used biomass-to-energy conversion process is the combustion, since the heat generated by this chemical process is easily used for cooking and heating. Although that thermal energy can be converted into electricity through a Rankine cycle, this process is not appropriate for rural areas, since it requires a lot of skilled maintenance, a complex management of the supply chain and it is economically sustainable only for medium/large-scale applications [8].
Another energy usage of the biomass is the production of fuel that can be used for running gas engine thus producing electrical energy. The process able to achieve this conversion varies according to the moisture content of the biomass itself. The most appropriate process for converting the dry biomass (humidity fraction $<$ 50%-60%) to fuel is the gasification process, whereas the ones for the wet biomass (humidity fraction $>$ 70%-80%) is the anaerobic digestion.

1.2.4.1 Gasificator

The gasification process is based on a partial combustion of dry biomass, with a limited air supply. The product is a combustible gas mixture known as *producer gas*, which contains carbon monoxide, hydrogen, nitrogen, carbon dioxide and methane, depending on the starting biomass composition. Generally, there are also high levels of tar and organic condensable; hence, the *producer gas* needs to be cleaned before being burned.

The lower heating value of this gas mixture is strongly affected by the type of biomass used, and it relies between 33,800-6,300 kJ/Nm [30]. Biomass gasification takes place in a cylindrical vessel and it is made up by four distinct stages: drying, pyrolysis, oxidation/combustion and reduction. There are many types of gasifiers, but the most used for small/medium-scale applications is the *fixed bed gasifier* [31]. A standard gasifier system for electrical production is composed by (see figure 1.8):

- Reactor, where the gasification takes place.
- Gas cooler, which reduces the gas temperature before entering the engine.
- Cleaning system, which removes the impurities of the *producer gas.*
- Engine coupled with an alternator, which produces the electrical energy through the gas combustion.
- Auxiliaries.

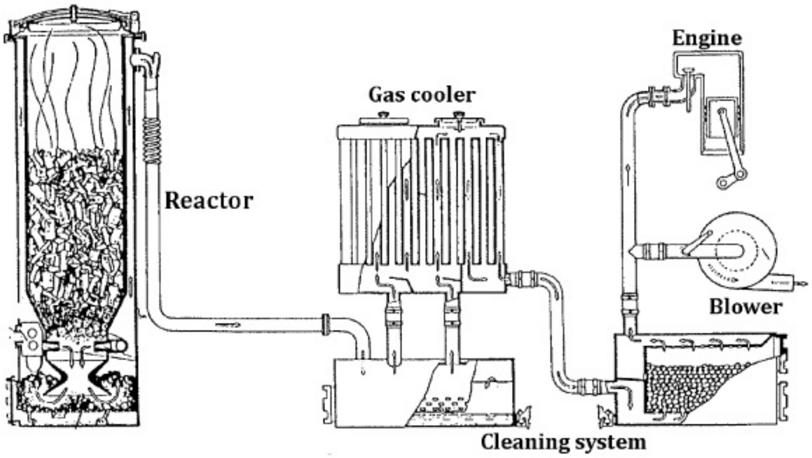


Figure 1.8: Schematic layout of a small-scale gasifier for electricity production [35]

The minimum size of those systems lies between 7 and 8 kW for technical reasons, with an energy efficiency within 10 and 20% [31, 32]. In a small-scale rural application, a gas engine can be directly coupled with the electrical load or can be employed in a mini-grid.

1.2.4.2 Anaerobic digester

The anaerobic digestion (AD) is the most appropriate method for converting wet biomass into energy. Almost everything that is considered organic waste is suitable for the AD process, if it is properly diluted by water. The result of this process is the *biogas*, which is mainly composed by methane and carbon dioxide.

The AD takes place in absence of oxygen in an enclosure called digester and it is composed by four phases, namely hydrolysis, acidogenesis (fermentation), acetogenesis/dehydrogenation and methanogenesis. For further information about the process, see [8].

The process is affected by several parameters, such as temperature, type of bacteria and chemical composition of the feed biomass. Moreover, the process temperature sets the type of bacteria used for the AD process: Psychrophilic (< 20°C), Mesophilic (20–40°C) and Thermophilic (40–60°C) [33].
Several different layouts of digester have been designed for small-scale applications, but it is out of the scope of this research to describe all of them. However, the *fixed dome digester* is now presented in order to achieve a deeper understanding of the process (see figure 1.9).
The diluted biomass is fed to the system and it reaches the digester, which is a cylinder with a fixed dome. There, the chemical reactions take place and the produced biogas is stored in the upper part. An outflow pipe allows the biogas to go towards the consumers. The biomass digested is collected in the outflow tank and it can be used as a fertilizer.

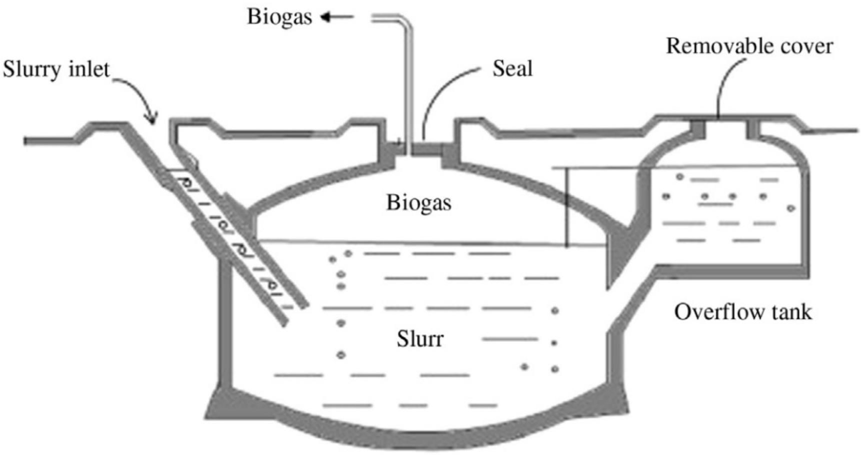


Figure 1.9: Layout of a fixed dome digester [34]

The biogas produced by an anaerobic digester is commonly used for cooking; however, it is also possible to produce electrical energy via a gas engine.

Chapter 2

Critical review of the state of the art of rural desalination

2.1 Introduction

As it was stated in section 1.1, in the next few decades, access to water will become an increasingly crucial challenge for many countries around the world, especially for rural areas. Many of these regions are located in coastal regions with access to an abundance of seawater. Furthermore, arid inland areas often have access to brackish groundwater. Therefore, seawater and brackish water, which form more than the 97.5% of the total global water reserves, might be an alternative source of water for several water-scarce regions, if properly treated with desalination processes [36, 37].

Desalination of seawater is known to be one of mankind's earliest forms of water treatment. It is a process in which saline water is separated into two flows using different forms of energy, one that has a low concentration of dissolved salts (fresh water), and the other which has a much higher concentration of dissolved salts than the original feed water (brine concentrate).

Water can be categorized according to its salinity level in three main categories: seawater, which has total dissolved solids (TDS) concentration of about 35,000 ppm or more; brackish water, with TDS concentration of 1,000 - 15,000 ppm and fresh water with concentration below 500 ppm, that is the permissible limit of salinity in drinkable water according to the World Health Organization (WHO) [38].

Literature overview

The following chapter presents a critical review of the state of the art of the desalination technologies appropriate for rural areas. The study is focused only on those technologies able to work without any connection to energy infrastructures and appropriate for very small-

($< 1\ m^3/d$), small- ($< 10\ m^3/d$) and medium-scale ($< 100\ m^3/d$) applications[1], that are currently experiencing an advanced stage of technological development (i.e. advanced R&D or application). For this reason, combinations of desalination technologies with geothermal and wave energy are not considered in the study, since the resulting systems are now at the first research stage and they seem appropriate only for large-scale applications. For more detail information on wave- and geothermic-powered desalination systems see [2, 39].

The current research relies on the analysis of 109 studies on desalination for off-grid desalination applications. Among them, 14 are review studies, 45 are studies on membrane desalination and 50 are studies on thermal desalination.

The 14 reviews are overall studies carried out in last decade[2] and they analyze and compare several desalination processes and their integration with renewable energies. These studies compare quite often renewable desalination systems with conventional ones; whereas, none of them is particularly focused on the peculiar context of the rural areas.

As it's pointed out by the diagram shown in figure 2.1, on one hand the majority of the studies considers the exploitation of different renewable sources, such as solar, wind, geothermal, etc; on the other hand, it is clear that the literature is currently giving special emphasis to solar energy: 5 of the 14 studies are focused only on direct and indirect solar desalination systems.

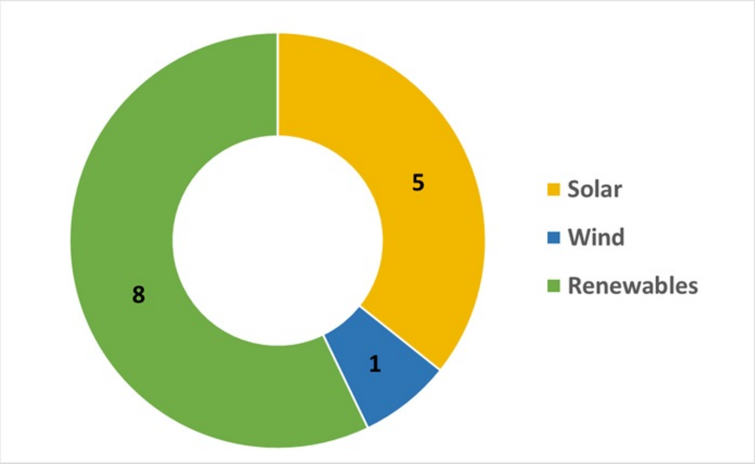


Figure 2.1: Energy focus of the analyzed review studies

The main membrane technologies are reverse osmosis (RO) and electrodialysis (ED). Among the 45 researches on membrane desalination, analyzed from the ones retrievable in

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[1] i.e. able to provide fresh water directly to the end-user (like an household), to a small groups of end-users (like a group of household) or to a small village, respectively

[2] from 2005 to 2015

the scientific literature in the last two decades, 30 are focused on RO process, 12 on ED and 3 on both technologies.

Figure 2.2 shows the different nature of the analyzed studies. Several studies concerning RO technology describe and examine real applications and on-field pilot units; whereas experimental studies on ED are carried out mostly in laboratory facilities, thus limiting themselves to test units of reduced size and to artificially reproduce different feed water qualities and operating conditions. As a matter of fact, this result mirrors the different technological development stage of the two technologies: small-scale RO units are fully commercially available technologies, whereas small-scale ED units are currently opening up to the market but they have limited practical experience yet.

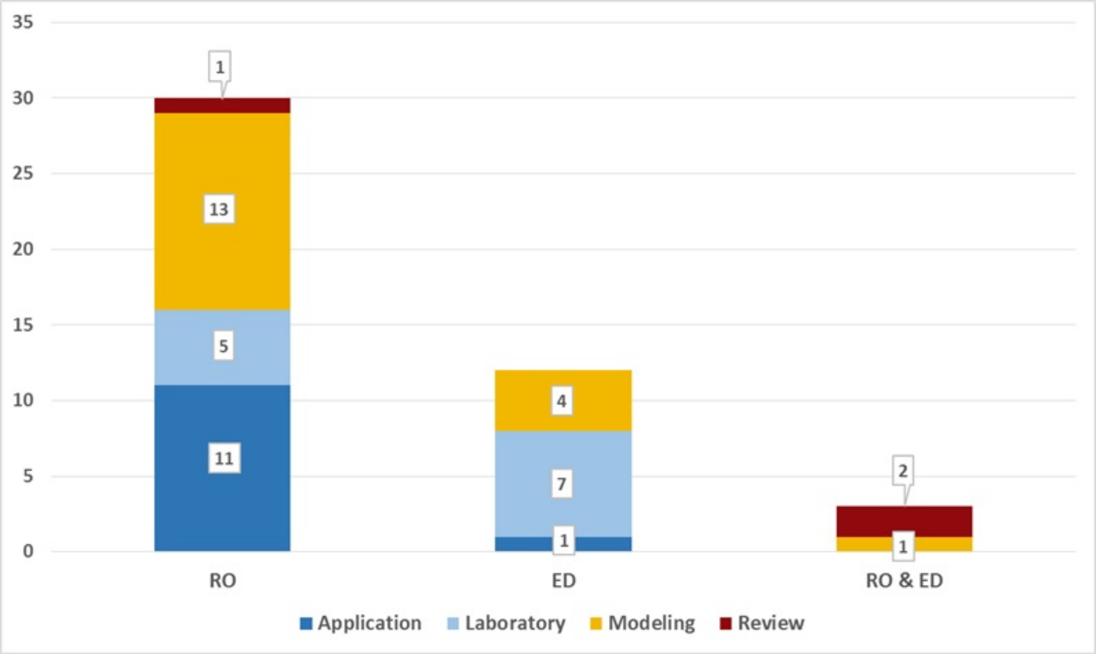


Figure 2.2: Overview on membrane desalination literature

As for the thermal desalination technologies, the attention is focused only on the ones appropriate for rural areas (see section 2.2). In particular, the current study analyzes Solar Stills (SS), Humidification-dehumidification (HDH) and Membrane Distillation (MD) technologies.

As shown in figure 2.3, among the 50 analyzed studies, 22 are focused on SS units and 23 on HDH process. It should be noted that several review studies on SS and HDH are retrievable in the literature, thus enlightening the existence of a plethora of different layouts, improvements and configurations that have been developed in the last two decades for both the technologies. Although MD is a very promising technology, less attention was given to this technology, because it is far from being commercialized.

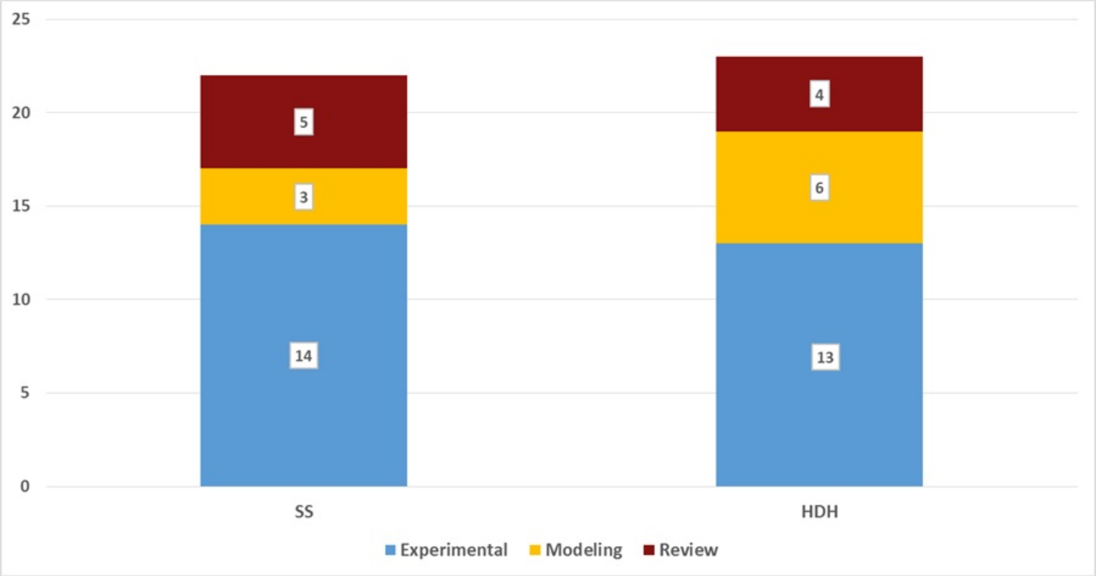


Figure 2.3: Overview on thermal desalination literature

Global desalination capacity and trends Water desalination technologies, available for decades, made great strides in many arid areas of the world, such as Middle East, the Mediterranean, and the Caribbean. In the first quarter of 2014, the total global desalination capacity stands at 81 million m^3/day. This is expected to reach over 100 million m^3/day by 2015 [40].

The increase in desalination capacity was caused primarily by increased water demand and by the significant reduction in desalination costs as a result of substantial technological advances which made desalinated water cost-competitive. In some specific areas, desalination is now able to successfully compete with conventional water resources and water transfers for potable water supply (e.g. construction of dams and reservoirs or canal transfers), since typical costs for conventional desalination technologies are about 1 €/m³ depending on the plant size, technology and raw water quality.

The vast majority of high production capacity plants are installed in the Middle East. Seawater desalination in the Gulf region represents 65% of global water desalination capacity: countries such as Qatar and Kuwait rely 100% on desalinated water for domestic and industrial supplies due to abundance of oil reserves [40]. As a matter of fact, despite desalination is a logical solution for many areas facing water scarcity, it is an energy-intensive process that usually relies on fossil fuels. The production of 1,000 m^3 per day of fresh water requires about 10,000 tonnes of oil per year, which can be considered a highly significant energy consumption, as it involves a recurrent energy expense which only few of the water-short areas of the world can afford [36].

On a global scale, in 2013, 68% of the desalinated water was produced by membrane

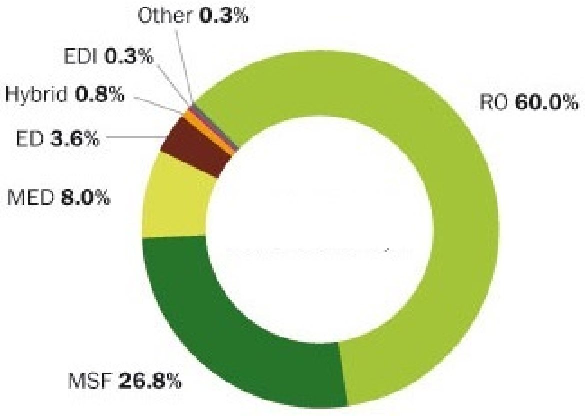


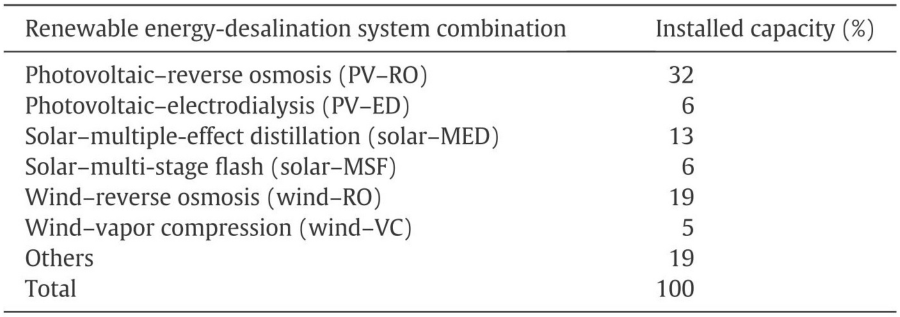
Figure 2.4: Installed desalination capacities by technology [43]

processes, which separate salt from water by means of semipermeable membranes, and 30% by thermal processes, which rely on the distillation of water by means of evaporation. Figure 2.4 shows the installed capacity of each main desalination technology in the first quarter of 2012. The membrane technology based desalination market is mostly dominated by reverse osmosis (RO), while the thermal market is in competition between MSF and multi-effect distillation (MED) [40].

Integrated renewable energy-driven desalination technologies Conventional desalination systems powered by fossil fuels produce environmental pollution and emission of greenhouse gases and they strongly depend on the unpredictable fluctuations of the oil and gas market prices. On the other hand, renewable energy systems are becoming increasingly reliable and mainstream with costs decreasing year-on-year, thus making renewable energy a viable energy option in many regions. Hence, recently, the utilization of renewable sources to drive desalination plants has emerged as a promising sustainable solution for freshwater supply in energy-short regions.

Currently, desalination powered by renewable energy is a very wide field that includes many technologies at various stages of technological development (see figure 2.5). Definitely, among the different renewable energies, solar and wind are the most-used energy sources. Unfortunately, current statistics on desalination shows that only 1% of total desalinated water is based on energy from renewable sources [36].

Desalination for rural areas People living in rural areas of developing countries, where electricity infrastructure is poor and supplies inadequate and unreliable, have neither the financial nor oil resources to rely on conventional desalination plants. However, frequently the



Renewable energy-desalination system combination	Installed capacity (%)
Photovoltaic–reverse osmosis (PV–RO)	32
Photovoltaic–electrodialysis (PV–ED)	6
Solar–multiple-effect distillation (solar–MED)	13
Solar–multi-stage flash (solar–MSF)	6
Wind–reverse osmosis (wind–RO)	19
Wind–vapor compression (wind–VC)	5
Others	19
Total	100

Figure 2.5: Distribution of renewable-powered desalination technology [40]

same remote areas suffering from shortage of drinking water sources have a significant renewable energy potential. Therefore, in remote and arid regions characterized by abundant RES potential and costly or not available access to conventional energy (fossil fuels and electricity), RES-powered off-grid desalination plants is an attractive alternative [36, 41, 42].

In particular, among all the possible technological solutions, the study, the development and the implementation of simple, flexible, small/medium-scale off-grid desalination systems is imperative if the population in such areas is to gain access to fresh and safe water supplies.

2.2 Thermal desalination

Thermal desalination, which relies on the distillation of water by means of evaporation, is the oldest technology employed by mankind to cleanse raw and salt water. The evaporation is fostered by an heat source such as fossil fuels, waste heat or solar thermal energy. The distillation by means of evaporation guarantee the fresh water quality, hence no feed water pre-treatment systems are usually needed in thermal desalination processes. A re-mineralization of the freshwater produced might be employed to improve the taste.

The most-used and mature thermal technologies are:

Multi stage flash (MSF) MSF plants typically range from 10,000 to 35,000 $\mathrm{m^3/day}$ [44]. They are composed by a series of stages - ranging from 4 to 40 - characterized by successively lower temperatures and pressures that cause flash evaporation of the hot feed water, thus producing vapour that will eventually condense as fresh water. It is an energy-intensive process, commonly powered by fossil fuels, especially in countries where the cost of oil and gas is very low (like the Arabic region). Despite the reliability of this technology, there is a growing concerning about its environmental impact and carbon footprint.

Multi effect distillation (MED) MED plants are composed by a series of stages, where cycles of evaporation and condensation occur. The size of MED units is generally between 600 to 30,000 $\mathrm{m^3/day}$ [44] and they employ both thermal and electrical energy. The earliest distillation plants were based on MED process, but MSF displaced it due to its lower costs. Today, there is a renewed interest in this technology, since it shows a better energy efficiency compared to the MSF, i.e the energy required by the MED process to produce 1 m^3 of fresh water is less than the one required by the MSF process.

Vapor compression (VC) Desalination plants using vapor compression rely on the heat generated by the compression of water vapor to evaporate salt water. The compression can be obtained through two methods: the mechanical vapor compression (MVC), which employes electricity, and the thermal vapor compression (TVC), which takes advantage of a thermal compressor. MVC is employed for medium-small applications (100-3,000 $\mathrm{m^3/day}$), whereas TVC is commonly used for large-scale plants (between 10,000-30,000 $\mathrm{m^3/day}$) [44].

These technologies are usually powered by fossil fuels. Due to their deep impact on the environment and their high operating costs, the scientific community is undertaking several projects focused on the coupling of solar thermal energy with desalination technologies [45]. Solar thermal systems are reported to be operated and maintained easier than conventional energy systems; therefore they are an appropriate option for powering desalination technologies in remote areas [46].

MSF, MED can be powered by solar energy via thermal collectors and photovoltaic panels. Although several studies on small-scale solar-powered desalination plants are reported in the literature [47, 48], these technologies do not seem to be appropriate for rural areas: MSF and MED are subjected to important economies of scale [49], thus the smaller-scale applications cannot achieve the performance of the large-scale units. Moreover, due to the presence of many pumps, pipes and different water loops, these technologies, together with the TVC one, are complex and they require a skilled maintenance, which is not usually available in rural areas. Furthermore, these technologies are sensible to intermittent operations, hence they require an heat storage in order to be able to be powered by solar thermal energy, thus increasing the complexity of the plant.

Therefore, the current study is focused only on the solar thermal desalination technologies especially appropriate for decentralized production, thus being characterized by low cost, low maintenance requirements, simple operations, as well as high reliability:

- Solar Stills (SS)
- Humidification-Dehumidification system (HDH)
- Membrane distillation (MD)

The main advantages of these technologies, in comparison with traditional ones such as MSF, MED and TVC, are that they are simple, compact, scalable and they operate at low temperatures. They do not require continuous operation, they can work with intermittent energy supply without additional modifications and energy storage, which makes them appropriate for an intermittent energy sources such as the solar one, without requiring a connection to the electrical grid [40].

It is also important to report the presence of studies on directly-wind-coupled MVC units in the literature; as matter of facts, they are a 100% renewable-powered solutions, appropriate for small/medium needs (up to 100 $^{\mathrm{m}^3}/_{\mathrm{day}}$), especially for small islands with abundant wind resource. However, due to technical issues, this technology is far from being commercialized, hence it can unlikely be a real option for rural water desalination in the short term [49, 50, 51]. Other innovative and promising technologies such as Freeze Desalination, Adsorption Desalination and Natural Vacuum Desalination are studied and reported in scientific studies [45, 52]; however, they are at the basic R&D stage of development, thus, without further improvements and studies, they cannot be currently accounted as technologies appropriate for rural areas.

In order to analyze the thermal desalination processes, it is important to define some physical quantities:

Thermal efficiency (η) The thermal efficiency of a thermal desalination process is define as the ratio of the latent heat of evaporation of the produced distillate to the solar radiation intensity over the device's receiving area:

$$\eta = \frac{\sum m\gamma}{AG}$$

Where $m\,[\frac{kg}{h}]$ is the hourly freshwater production, $\gamma\,[\frac{kj}{kg}]$ is the vapor latent heat, $A\,[m^2]$ is the absorber area surface and $G\,[\frac{W}{m^2}]$ is the solar radiation intensity over the area.

The thermal efficiency measures the overall efficiency of the device, considering both the solar radiation collection system's and the distillation process performance.

If the system is able to recover the thermal energy of the produced fresh water, this parameter might be greater than 1.

Gained Output Ratio (GOR) The gained output ratio of a thermal desalination process is defined as the ratio of the latent heat of evaporation of the produced distillate to the total energy absorbed by the solar collectors system:

$$GOR = \frac{\sum m\gamma}{E_{in}}$$

Where E_{in} is the energy input to the system.

This parameter measures only the efficiency of the distillation device and the performance of the energy recovery, without considering the efficiency of the solar thermal collectors. Achieving an higher GOR implies having better thermal performance and less heat consumption. The GOR of traditional fossil-fueled desalination plants ranges between 8 to 16, that implies an energy consumption rate of $\sim 282 - 145$ kj/kg [44].

Although the GOR is a less complete index than the thermal efficiency, it can be effectively used to compare different solar-based distillation technologies, without considering the efficiency of the solar collectors.

Specific water production (SWP) The specific water production index considers the amount of fresh water produced per m^2 of absorber area per day $[\frac{l}{m^2 day}]$. It is defined as:

$$SWP = \frac{m_{daily}}{A}$$

Where m_{daily} is the average daily production $[\frac{l}{day}]$.

SWP gives an indication of the overall efficiency of the considered desalination technique. Systems with higher specific water production require less area and they are less capital-intensive.

Recovery ratio (RR) The recovery ratio - also known as *extraction efficiency* - is defined as the ratio of fresh water produced to the amount of salt water fed into the system. Low recovery ratio implies higher brine discharge flow. The advantage of a low recovery ratio is that complex feed flow pretreatment or brine disposal processes may not be required. However a low recovery ratio also implies higher amount of feed water, thus requiring higher plants volumes and more powerful pumps.

Water production cost (WPC) The water production cost is the average cost per m^3 of water produced by the device during the lifetime:

$$WPC = \frac{C_{tot}}{m_{tot}}$$

Where:

- C_{tot} is the total annualized cost of the system, which is the sum of each annualized cost related to the system. Therefore, it includes capital cost (spread over the project lifetime), operation and maintenance costs and replacement costs.
- *Total water production* is the amount of water produced during the project lifetime.

The WPC is the most crucial economic parameter in the evaluation of a desalination system, since it takes into account both capital and operating costs.

2.2.1 Solar still

2.2.1.1 Overview

A solar still is basically a low-tech *greenhouse*, characterized by simplicity of construction and maintenance (see figure 2.6). The operational principle is based on the evaporation of the salt water fostered by the greenhouse effect.

A solar still is a simple and mature technology and it has been used for centuries, with many available models available on the market [53]. It is mainly employed to provide fresh water to remote rural areas [39] and in life raft's survival kits. The unit size is below 100 $^{L}/_{day}$, since the performances of this device drop with the production capacity. In addition, these devices are not subject to economies of scale, hence there is not benefit in building larger solar stills. However, the specific water production is very low, ranging from 3 to 6 $^{L}/_{m^2 day}$.

2.2.1.2 The solar still process

The operational principle is based on the fact that glass, as well as other transparent materials, has the property of transmitting incident short-wave solar radiation. The incident solar radiation is transmitted through the transparent cover and it is absorbed as heat by a black surface in contact with the salt water to be distilled. The non-absorbed radiation is reflected as a long-wave radiation, thus being caught by the glass cover (the so-called *greenhouse effect*). Hence, the water is heated thanks to the captured solar radiation and it partially evaporates. The vapor condenses on the glass cover, which is at a lower temperature because it is in contact with the atmosphere, and it then runs down into a groove from where it is collected.

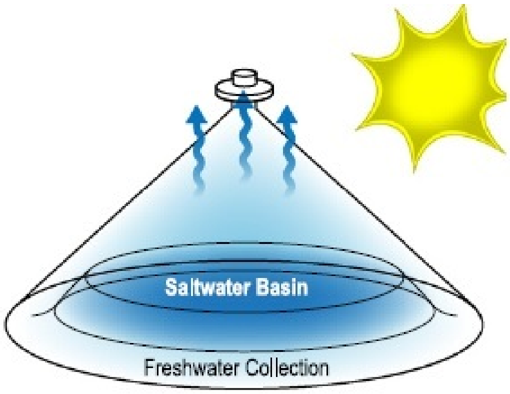


Figure 2.6: Schematic layout of a basic solar still [44]

It is not necessary to boil water to distill it: simply elevating its temperature, at values lower than its boiling point, will adequately increase the evaporation rate. De facto, although vigorous boiling hastens the distillation process, it can also force unwanted residue into the distillate, thus lowering the water quality.

Solar stills are classified in two different categories: passive and active. In the case of passive stills, the water is only heated by the solar radiation hitting the solar still basin surface. In the active solar still instead, the water is preheated by another source of energy (i.e. a solar thermal collector, the recirculation of the discharged brine and others), before entering the basin.

2.2.1.3 Factors affecting the productivity and layouts

Since the solar still technology is very simple, the literature reports a plethora of different layouts, most of them more efficient but also more complex and expensive than the basic one. Although each development might enhance the solar still productivity, it is also crucial to consider the cost of those improvements and their effects on the simplicity of the technology. A less efficient, but cheaper and simpler solar still is generally more appropriate for rural areas than a very complex one. Therefore, it is beyond the scope of this study to show all the existing solar still layouts.

However, it is important to understand the factors affecting the productivity of the solar still and hence to present some different layouts designed to modify them. A wider set of layouts is described in [54].

Free surface water area

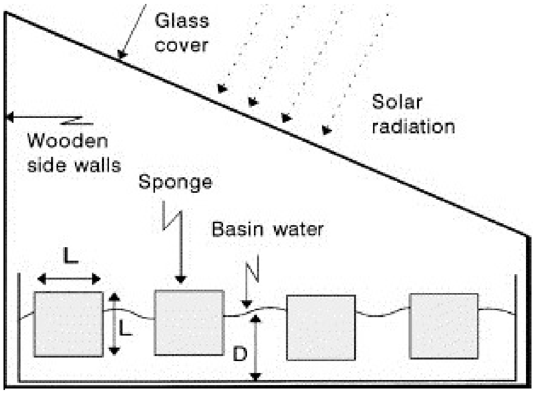


Figure 2.7: Schematic layout of a solar still with sponges [55]

The evaporation rate of the water in the solar still is directly proportional to the exposure area of the water. Thus, the productivity of the solar still increases with the free surface area of the water in the basin. Bassam et al. [55] used sponges to increase the free surface area of the water as shown in figure 2.7. The sponges suck the basin water via capillarity effect, thus increasing the surface area over which water evaporation occurs. The employment of sponges might increase the distillate production up to 273%, compared with a basic solar still operating under the same condition.

Water-glass temperature difference

The freshwater production of a solar still is strongly affected by the temperature difference between the glass cover and the water: as a matter of facts, the condensation is driven by this difference of temperature. A double basin solar still where the water is made available in both basins, was fabricated by Zurigat et al. [56] (see figure 2.8). This layout allows to increase the glass-water temperature difference, since the glass layer of the lower level is cooled by the above salt water. Moreover, the latent heat of condensation of the lower level is employed to heating up the salt water of the upper level. This configuration is reported to enhance the production of fresh water by 20%.

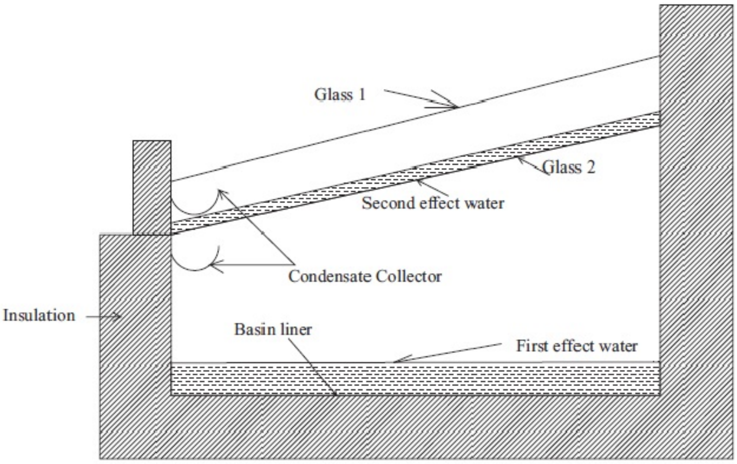


Figure 2.8: Schematic layout of a double basin solar still [56]

Area of absorber plate

The energy source of the solar still is the solar radiation absorbed by the bottom plate. The energy captured by the plate is proportional to the area of the absorber plate itself, hence the addition of fins to the bottom plate might enhance the freshwater yield (by 20%, according to Velmurugan et al. [57]).

However, it is difficult to increase the absorber plate area without increasing the area required for the installation of the solar still. In order to overcome this issue, a possible solution is to add to the solar still internal or external reflectors able to concentrate the radiation over the absorber plate. Tanaka [58] proposed a single basin still with internal and external reflectors, as shown in figure 2.9, consisting of a basin liner with internal reflectors, a glass cover and an external reflector. Compared to the conventional solar still, more solar radiation is introduced into the still by the reflectors: the daily productivity can be increased up to 70–100% on winter days.

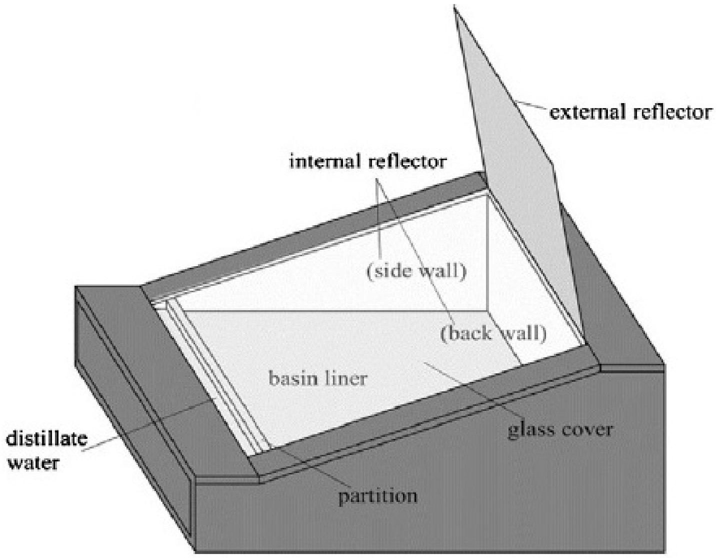


Figure 2.9: Schematic layout of a single basin solar still with reflectors [58]

Temperature of the feed water

The evaporation rate grows with the temperature of the feed water, hence several attempts have been made to increase it. The literature reports several studies about the employment of solar collectors for preheating the water fed to the solar still [59, 60], in order to achieve better yields. Sampathkumar et al. [61] studied the behavior of a system composed by a single basin solar still, coupled with an evacuated tube collector and a storage tank (see figure 2.10). They report an increase of 77% of the freshwater yield, whereas the overall efficiency of the system results to be lower than the one of a basic solar still.

Solar energy is intermittent by nature and its intensity depends on daily time, meteorological conditions, geographical location, etc. An heat storage is able to supply the solar still with hot water, even when the solar radiation is not available, thus maximizing the exploitation of the solar radiation. It is also possible to produce fresh water by night, if the heat storage is properly charged.

The simplest way to store the heat coming from the solar radiation is through a hot water storage tank [60]. Other authors propose to use sandy heat reservoir [62], phase change materials storage [63] and shallow solar ponds [64]. According to El-Sebaii et al. [64], an active solar still coupled with a shallow solar pond might increase the efficiency up to 54%.

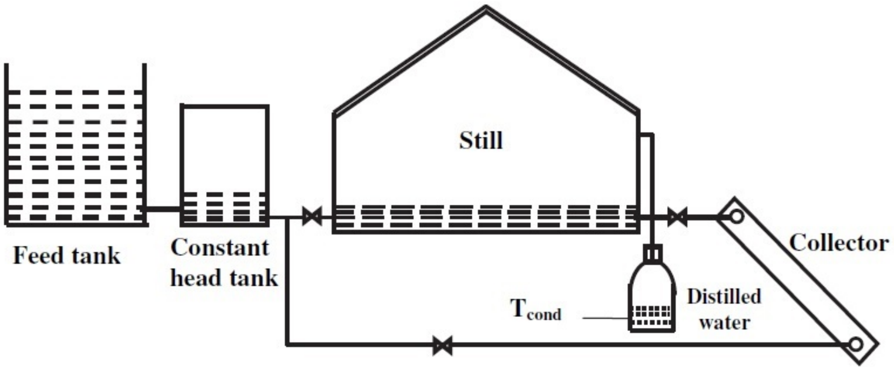


Figure 2.10: Schematic layout of a basin solar still coupled with evacuated tube collector [59]

Depth of water

According to the literature, the freshwater yield decreases with the increase of the water depth above the basin. Therefore, the goal is maintaining the water depth at the minimum value, while avoiding dry spots. Omara et al. [65] studied a one basin solar still, coupled with an evacuated tube collector, and equipped with wicks (see figure 2.11).

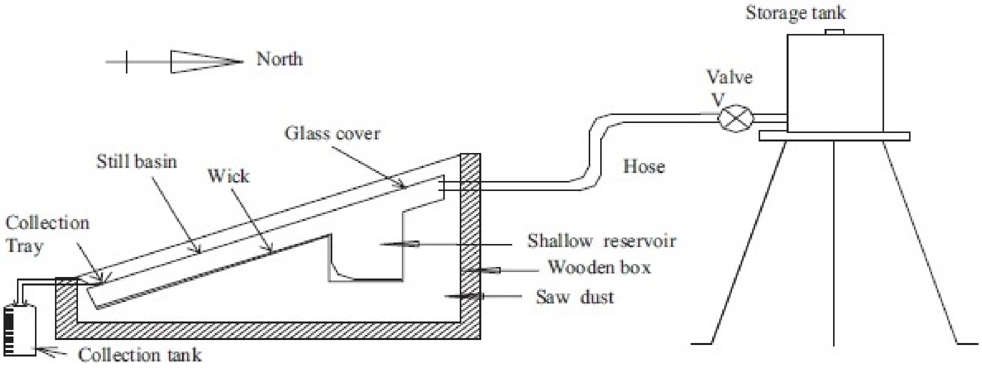


Figure 2.11: Schematic layout of a wick type solar still [66]

The wicks suck the brine from the shallow reservoir through capillary action, and they displace it all over the basin, thus keeping the brine as shallow as possible while avoiding dry spots. The brine is then driven downward by gravity. The authors reported that a double wick layer solar still has a productivity higher by 215% than a single basin solar still. However, the wicks have to be replaced several times throughout the solar still's lifetime, due to their rapid degradation.

Weir-stepped solar stills are designed to minimize the water depth while avoiding dry spots (see figure 2.12). They are reported to be more reliable than the stills taking advantage of the wicks [67]. The brine flows from the highest tray to the lowest by means of gravity, thus filling the weirs at each level. Therefore, each level of the stepped solar still is filled with the appropriate quantity of brine. Tabrizi et al. [67] studied a weir-stepped solar still, equipped with a phase change material heat storage . They reported a specific production of 4.85 $\frac{l}{m^2 day}$ for the system with heat storage.

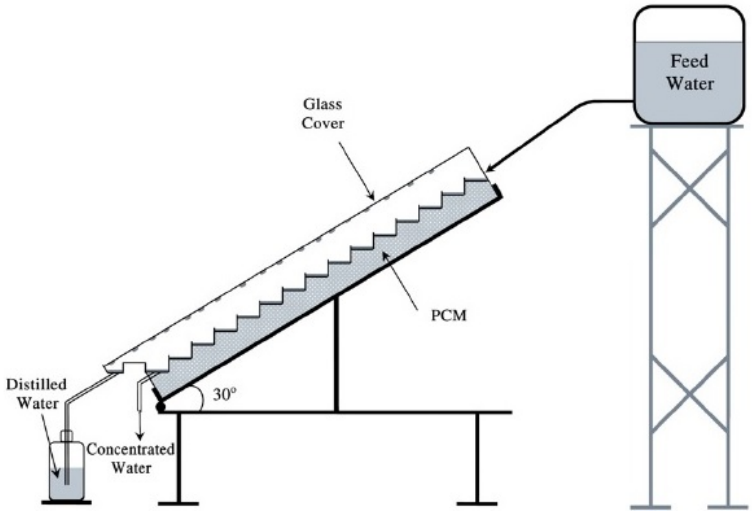
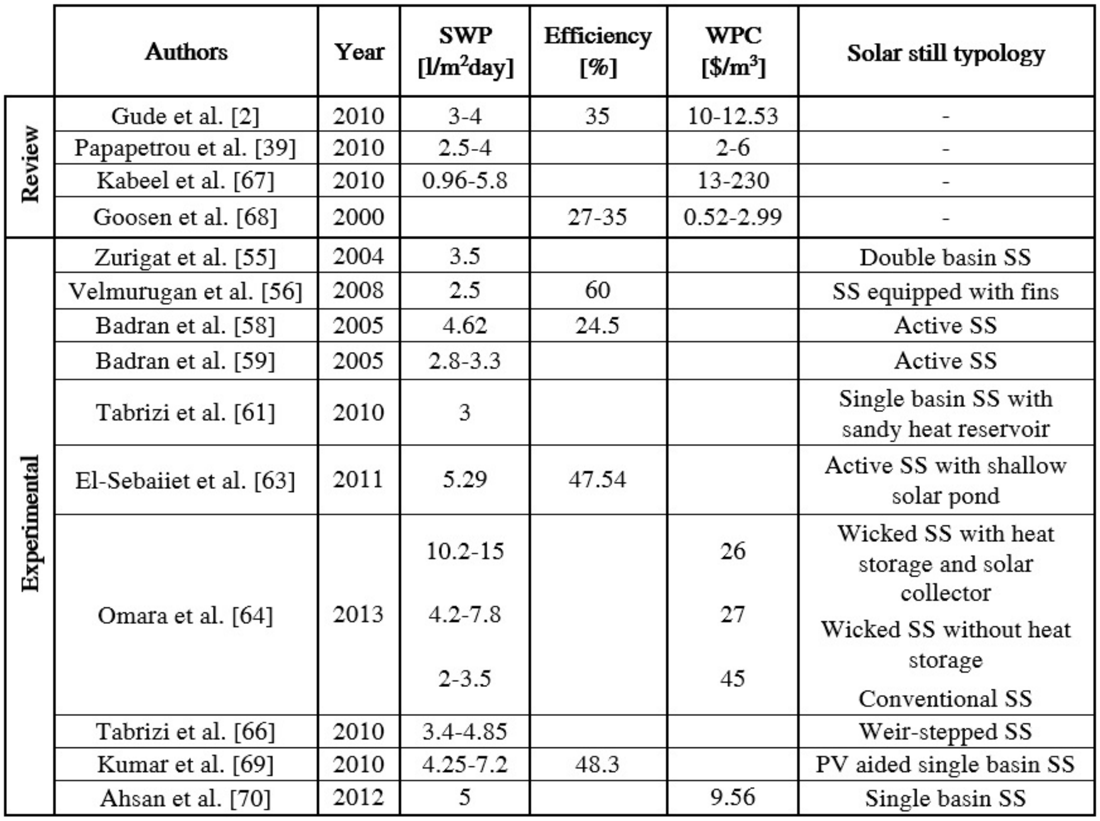


Figure 2.12: Schematic layout of a weir-stepped solar still [67]

2.2.1.4 Techno-economical features

A solar still is a simple, reliable and mature technology. It presents some specific advantages for its usage in rural areas, due to its easier construction using local available materials, its minimum operation and maintenance requirements and its friendliness to the environment. As a matter of facts, the maintenance only consists in cleaning the surface basin and the glass, and the solar still's materials can be easily retrieved in rural areas. Commonly, the most-used materials are Polythene plastic and glass for the cover and black rubber or asphalt mats for the lining of the absorption plate [54]. If the asphalt is used, it must be sealed, for example with a silicon rubber, to avoid the water contamination

As for the quality of the fresh water produced, the distillation should guarantee the freshwater quality; however, a potential source of contamination include substances present in the air inside the distiller, and in the lining or coating of the evaporating pan, which might somehow find their way into the water condensing on the underside of the cover glass. Nevertheless, the water quality can be ensured by selecting non-toxic materials for assembling the still, and by preconditioning the distiller by "baking" it under the sun for several days, in order to drive off most of the volatiles [49].



	Authors	Year	SWP [l/m^{2}day]	Efficiency [%]	WPC [\$/m^3]	Solar still typology
Review	Gude et al. [2]	2010	3-4	35	10-12.53	-
	Papapetrou et al. [39]	2010	2.5-4		2-6	-
	Kabeel et al. [67]	2010	0.96-5.8		13-230	-
	Goosen et al. [68]	2000		27-35	0.52-2.99	-
Experimental	Zurigat et al. [55]	2004	3.5			Double basin SS
	Velmurugan et al. [56]	2008	2.5	60		SS equipped with fins
	Badran et al. [58]	2005	4.62	24.5		Active SS
	Badran et al. [59]	2005	2.8-3.3			Active SS
	Tabrizi et al. [61]	2010	3			Single basin SS with sandy heat reservoir
	El-Sebaiiet et al. [63]	2011	5.29	47.54		Active SS with shallow solar pond
	Omara et al. [64]	2013	10.2-15 4.2-7.8 2-3.5		26 27 45	Wicked SS with heat storage and solar collector Wicked SS without heat storage Conventional SS
	Tabrizi et al. [66]	2010	3.4-4.85			Weir-stepped SS
	Kumar et al. [69]	2010	4.25-7.2	48.3		PV aided single basin SS
	Ahsan et al. [70]	2012	5		9.56	Single basin SS

Table 2.1: Techno-economic features of solar still units

However, the main drawback of this technology is the lower amount of distilled water producible in comparison with other desalination systems. As a matter of facts, the specific water production of a basic still is in the range of few liters per square meter, thus making the system generally very expensive. Moreover, the low specific production of the solar still leads to a large amount of area required for the installation of the equipment [66].

Table 2.1 shows the water production cost (WPC, $\frac{\$}{m^3}$), the efficiency ($\eta$) and the specific water production of different solar still reported in literature. The studies have been chosen endorsing the most updated and reliable ones.

It is important to remark that the values of the reported parameters are strongly affected by environmental conditions, local equipment prices, energy costs and authors assumptions. Therefore, the water production cost ranges on the average in a quite broad span: 2-15 $\frac{\$}{m^3}$. The specific water production instead, ranges generally between 3-7 $\frac{l}{m^2 day}$. It should be noted that the efficiency is commonly low, due to the loss of the latent heat of condensation on the glass cover.

2.2.1.5 Final considerations

Solar stills might be an appropriate solution for the water scarcity in rural areas, thanks to:

- Simplicity of the technology: everyone is able to properly manage it, without having any particular skill.
- Simplicity of the design and construction: solar stills can be built using local manpower and materials, thus enhancing the acceptability of the technology in the local community. It would be possible also to easily teach to the local communities how to build solar stills, in order to make them able to provide themselves with these devices.
- The size: solar stills do not experience particularly economies of scale, thus their size is usually very small. Therefore, they are appropriate for a home-based water distribution, where every household manages its own solar still.
- Not affected by the feed water quality: solar stills can treat brackish water as well as seawater, with no effects on the energy requirements. The feed water does not need a pretreatment system, thanks to the effect of the distillation by means of evaporation.
- The single basin solar still is a well-proven technology, already available on the market.

However, it is also crucial to underline the main drawbacks of this technology:

- Very low specific yield: solar stills presents the lowest value of the specific water production, among the thermal desalination technologies. In order to produce the water needed by a small village (about 6,000 $\frac{l}{day}$), using a standard solar still with an absorber plate of 1 m^2 and a specific water production of 4 $\frac{l}{m^2 day}$, 1,500 devices would be needed.
- High water production cost: due to the very low productivity, the water production cost is higher than other desalination technologies. However, the cost might be reduced using local materials and manpower.
- Very low thermal efficiency

In conclusion, solar stills are a viable option for rural desalination, especially if built using local materials and manpower. Its drawbacks must be considered, in particular the low specific water production and the high water production cost.

2.2.2 Humidification-deumidification cycle

2.2.2.1 Overview

The humidification-deumidification (HDH) process can be considered a development of the solar still technology. Several HDH units have been built all over the world for research purposes and the technology is now reaching the commercial stage [39]; as a matter of facts, some companies have already put this technology on the market [72]. Several studies are focused on the multi-effect-humidification (MEH) process, which is based on the same principle of the HDH. The term "multiple effect" does not necessary refer to well distinguished stages, but to the fact that evaporation and condensation happen continuously over the whole temperature range between the condenser inlet and evaporator outlet.

The source of inspiration of the HDH operation principle comes from a natural phenomena: the *rain cycle*. In the rain cycle, seawater is heated by the sun and it humidifies the air which acts as a good gas carrier, since the carrying capacity of a gas like air grows with its temperature. After that, the humidified air rises, thanks to his lower density, and it forms clouds. The cycle ends when clouds become rain, that is the "dehumidification" of the carrying air. The artificial version of this cycle is called humidification-dehumidification desalination cycle. Usually the unit size ranges between 1-100 $^{m^3}/_{day}$, therefore it is appropriate for medium/small-scale application. A sketch of a basic HDH unit is presented in figure 2.13.

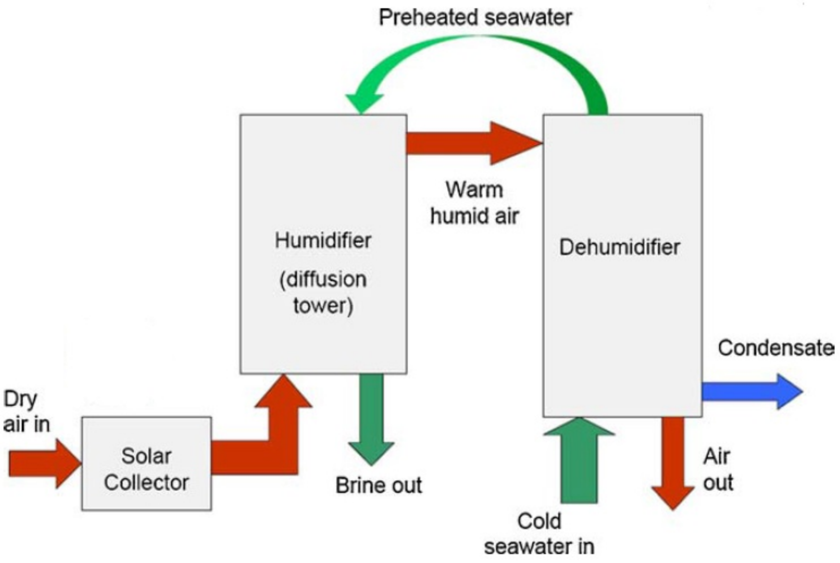


Figure 2.13: Schematic layout of a HDH process [73]

2.2.2.2 The HDH process and classification

A HDH unit is made up by three subsystems (see figure 2.13):

- the air and/or the water heater, that is the only section that exchanges energy with an external body (neglecting the thermal losses);
- the humidifier (or evaporator), where the distillation occurs;
- the dehumidifier (or condenser), where the fresh water is collected.

Usually a small PV-powered pump is employed to feed the system.

The principle of the HDH technology can be implemented in several ways. It is possible to classify the different configurations by (see diagram in figure 2.14):

- Cycle configuration: Closed Air Open Water, Closed Water Open Air.
- Type of heating: water heating, air heating or a combination of the two.
- Forced or natural convection if the air loop.

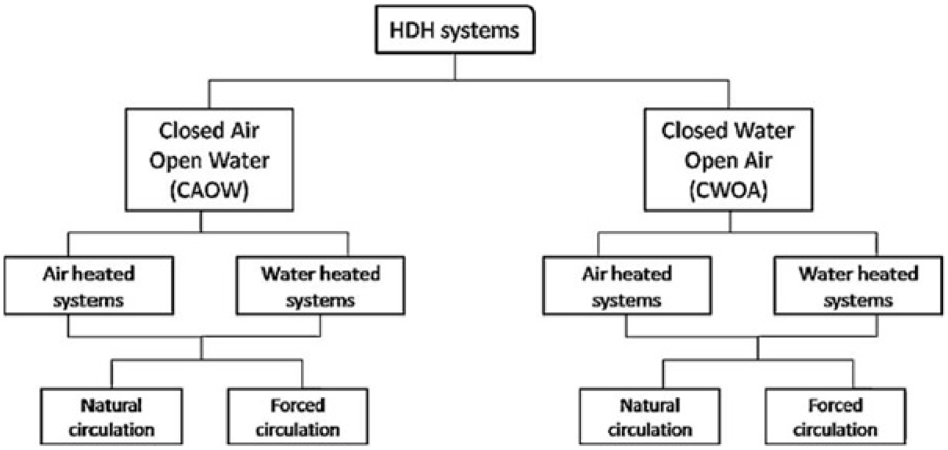


Figure 2.14: Classification of the HDH cycles [73]

Closed air open water (CAOW) water-heated systems Figure 2.15 shows a CAOW water-heated plant layout. The hot water coming from the solar collectors is fed into the humidifier. Thanks to the thermal energy carried by the stream of hot water, the air gets heated and humidified (line 1-2 on the psychometric chart reported in figure 2.15); then it passes through the dehumidifier, where the condensation occurs thanks to the difference of temperature between the incoming heated air and the salt water. As a matter of facts, the feed water acts like a coolant and gets preheated by the latent heat of the incoming wet air. Then, the preheated water crosses an array of solar collectors, in order to close the cycle. After the loss of humidity, the air returns to the humidifier following a closed loop that can be driven by natural or forced convection (line 2-1 in figure 2.15). The discharged brine is eventually collected on the bottom of the humidifier, whereas the fresh water on the other side of the system. CAOW water-heated systems are the oldest and most-studied type of HDH process.

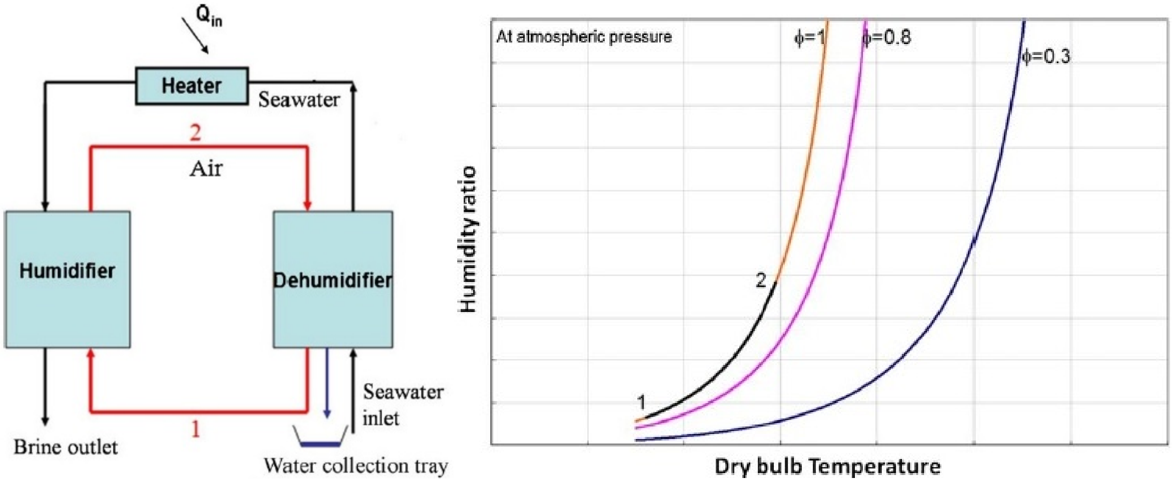


Figure 2.15: CAOW layout and psychometric chart [73]

Closed water open air (CWOA) water-heated systems Figure 2.15 shows a typical CWOA unit layout. Feed water follows a closed cycle, in which it is firstly heated through the solar collectors and then it heats the incoming air in the humidifier. Finally, it acts as a coolant for the humidified air, in order to foster the condensation of the fresh water and to recover the latent heat of the air humidity. Since there is a continuous loss of water due to the condensation of the humidity, the system must have a blow down and a makeup flow. On the other hand, air is taken from the environment and, after passing through the cycle, it is released to the ambient. The humidification process is shown in the psychometric chart: line 1-2 in figure 2.16. The air entering at ambient conditions is saturated in the humidifier (point 2 on the psychometric chart 2.16). Then it crosses the dehumidifier, where the condensation of the humidity occurs (line 2-3).

This configuration it is not currently attracting a wide interest [73]. The main drawback of this layout is that the freshwater production is strongly affected by local environment and also by the efficiency of the humidifier. As a matter of facts, if the humidifier does not cool enough the water flow, due to an high relative humidity of the atmospheric air, the incoming coolant water in the dehumidifier will reach an higher temperature, thus limiting the condensing rate and the freshwater production. On the other hand, if the system works at its optimal conditions, the water flow can be cooled below the ambient temperature (until the dew point), thus enhancing the freshwater production. For this reason, the CWOA can achieve better performance than a CAOW.

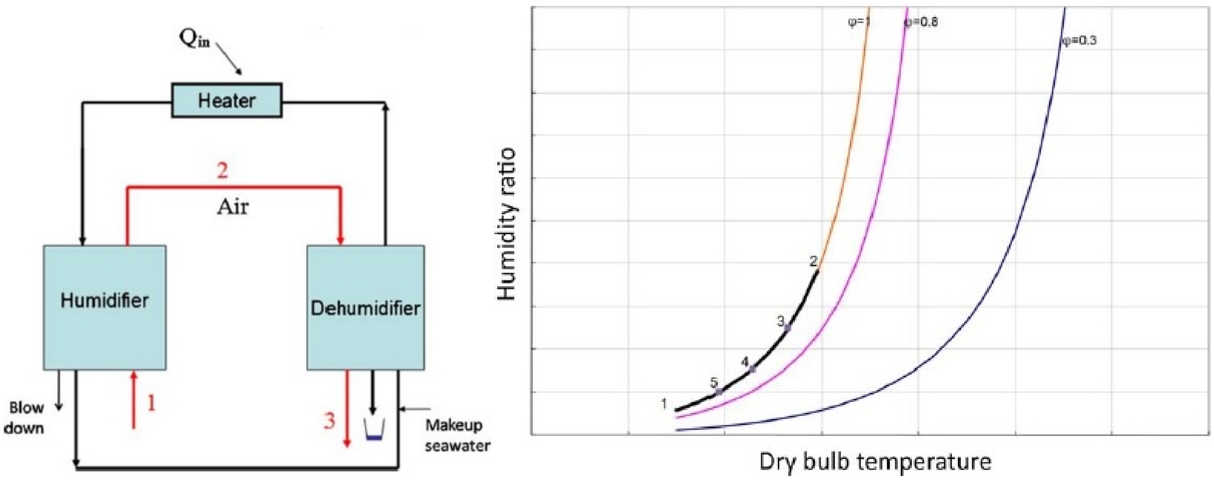


Figure 2.16: CWOA layout and psychometric chart [73]

Closed air-open water (CAOW) air-heated systems Scientific literature shows a remarkable interest on this system [73, 74], which is presented in figure 2.15. The air following a closed cycle is heated up to 80°-90°C thanks to the solar collectors (line 1-2 in figure 2.17). Then the heated air passes through the humidifier, where it gets cooled and saturated (line 2-3). Finally, it enters the dehumidifier where it loses humidity (line 3-1).

The main drawback of this system is that the absolute humidity carried by the air at this operating temperature is very low, thus reducing the productivity of the cycle. In addition, solar air heaters are less efficient than solar collectors. Therefore, it is reported that CAOW air-heated systems have an higher energy consumption than the water-heated one, thus implying higher water production cost and more area required.

Other advanced plant layouts such as multi-stage HDH and multi-injection HDH are analyzed in the literature. However, it is beyond the scope of this study to show all the existing advanced layouts since they are less appropriate for the rural context than the basic ones. For further information on the two advanced layouts see [75, 76].

2.2.2.3 Techno-economical features

The HDH process has several strong points, which include flexibility in capacity, moderate installation and operating costs, simplicity and the possibility of using low-grade thermal

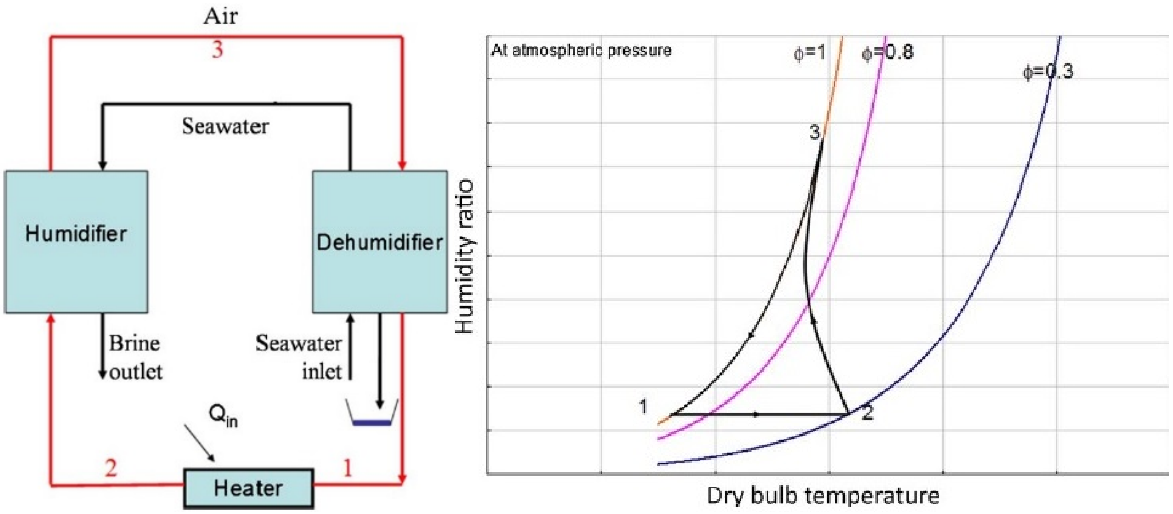


Figure 2.17: CAOW air-heated layout and psicometric chart [73]

energy [77]. Therefore, it is especially appropriate for a decentralized water production in rural areas.

As it was already stated, the HDH technology can be considered a development of the solar stills. The most important weakness of solar stills is the low efficiency per square meter, which implies a large amount of area required, even for a modest water production. This drawback depends on the loss of the latent heat through the glass cover. The HDH cycle tries to resolve this weakness by dividing each step (solar absorption, evaporation, condensation and heat recovery) in different physical parts (humidifier, dehumidifier and solar collectors).

The energy demand of the HDH cycle is mostly thermal energy; however, it also requires a small amount of electrical energy for the circulation pump, and, optionally, for air ventilation. Hence, usually a small PV system powering pumps and ventilators is associated to the HDH cycle. It should be noted that the need for electrical energy introduces a complication in the plant layout, which is not present in the case of solar stills.

According to the reviewed literature, it is possible to make some general statements regarding the technical behavior of the HDH cycle:

- The specific water production is a crucial parameter: increasing this parameter leads to higher freshwater production, to fewer solar collector's area, and to less capital cost of the system.

- A better insulation from external environment leads to a better thermal performance (GOR).

- Higher temperature of the water/air coming out from the solar collector can improve the productivity. This phenomena is strongly affected by the performance of the solar collectors, which are less-efficient with the increasing of the working temperature.

- Lower temperature of the coolant water leads to higher condensation flow rate, thus increasing the specific water productivity.
- Improving the heat exchange between the heated water/air with the cold air/water enhances the thermal performance (GOR).
- Forced circulation in CAOW systems can weakly improve the heat exchange. However, the forced circulation requires additional electrical ventilators, thus implying an increase of the costs and complexity of the plant.
- The feed water does not require a pretreatment system, thanks to the effect of the distillation by means of evaporation. However, if the carrying air is polluted, the produced water quality might decrease. A pre-filtration system might be used to remove solid particles, in order to protect the circulation pump.

The HDH technology is at a pre-commercial development stage [39]; therefore, it is difficult to define an accurate range of GOR, of specific water production and of water production cost. Moreover, those parameters are strongly affected by the different environmental conditions and test methodologies.

Table 2.2 reports the water production cost ($\$/m^3$), the GOR and the specific water production of different pilot units reported in the reviewed literature. The studies were chosen endorsing the most updated and reliable ones, as for the solar stills.

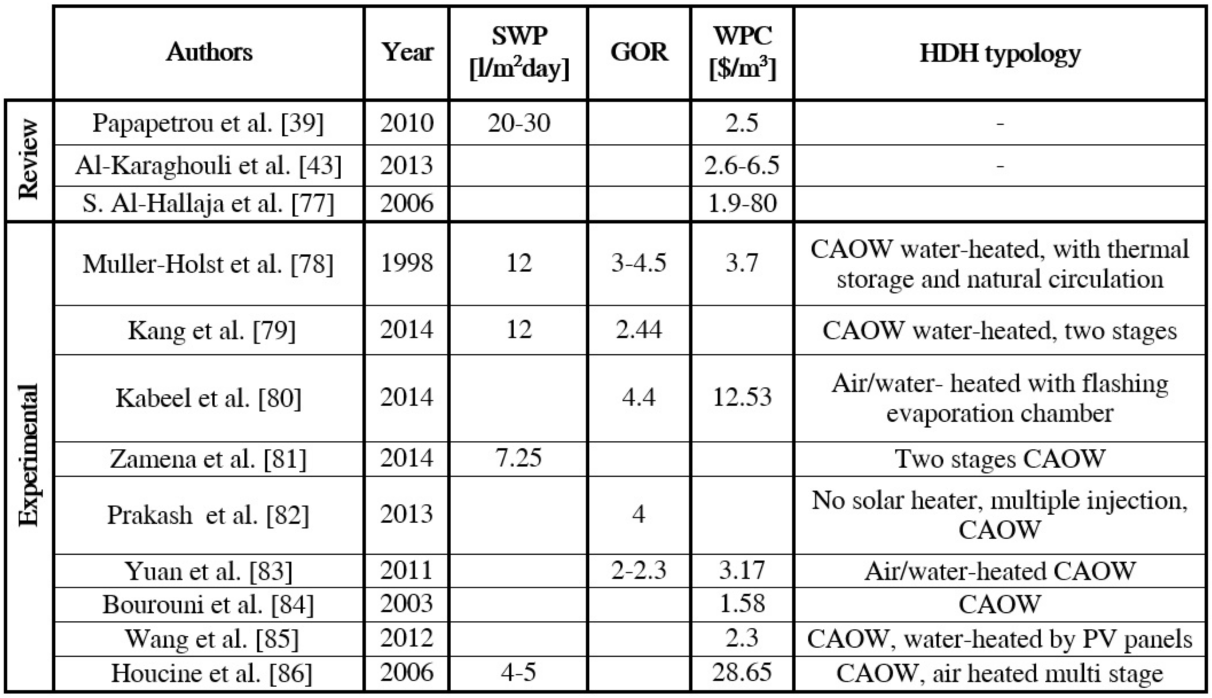
As table 2.2 shows, the specific water production is much higher than solar stills, as well as the GOR. The water production costs ranges between 2-13 $\$/m^3$; however these values might strongly change according to the local market peculiarities and by the environmental conditions. The specific water production commonly ranges between 7.25 to 20 $^{\mathrm{L}}/_{\mathrm{m^2day}}$, while the GOR lies between 2-4.5. This GOR implies lower performance in comparison with traditional technologies like MSF, which has a GOR equal to 8.

2.2.2.4 Final considerations

HDH technology might be an important solution to water scarcity in rural areas, due to the following features:

- It has comparable simplicity with the solar stills, hence requiring no advanced technical skills for its maintenance; but it is more productive (about 300% higher).
- It is a very solid device, since it has no moving parts (except for a low pressure pump or an optional air convector). Moreover, the solar collectors are very reliable.
- It is especially suitable for low-medium production, like the ones required by rural areas.

However, its main drawbacks have to be considered:



	Authors	Year	SWP [l/m²day]	GOR	WPC [$/m³]	HDH typology
Review	Papapetrou et al. [39]	2010	20-30		2.5	-
	Al-Karaghouli et al. [43]	2013			2.6-6.5	-
	S. Al-Hallaja et al. [77]	2006			1.9-80	
Experimental	Muller-Holst et al. [78]	1998	12	3-4.5	3.7	CAOW water-heated, with thermal storage and natural circulation
	Kang et al. [79]	2014	12	2.44		CAOW water-heated, two stages
	Kabeel et al. [80]	2014		4.4	12.53	Air/water- heated with flashing evaporation chamber
	Zamena et al. [81]	2014	7.25			Two stages CAOW
	Prakash et al. [82]	2013		4		No solar heater, multiple injection, CAOW
	Yuan et al. [83]	2011		2-2.3	3.17	Air/water-heated CAOW
	Bourouni et al. [84]	2003			1.58	CAOW
	Wang et al. [85]	2012			2.3	CAOW, water-heated by PV panels
	Houcine et al. [86]	2006	4-5		28.65	CAOW, air heated multi stage

Table 2.2: Techno-economic features of HDH units

- Although the HDH's water production cost might be lesser than the solar still's one, this technology is more expensive than traditional desalination processes.
- HDH is at a pre-commercial state. There are few companies that are currently employing this technology [72]; hence, the market is not mature.
- It cannot be employed for home-based freshwater distribution.
- It needs a small amount of electrical energy for the feed pump, which can be provided by photovoltaic panels, thus increasing the water production cost.

The HDH technology has better performance than solar stills and it is appropriate for rural areas thanks to its simplicity. However, it is not yet a mature technology, and the water production cost is still too high. More research, which can hopefully result in lower production cost, must be carried out in order to enhance its competitiveness and sustainability.

2.2.3 Membrane distillation

2.2.3.1 Overview

Membrane Distillation (MD) is a promising technology for desalting highly saline water.

In a MD process water is transported between an hot and a cool stream separated by a membrane permeable to water vapor only; hence, it is able to exclude the transition of liquid phase and of dissolved particles[3] (see figure 2.18). The exchange of water vapor is carried out by a small temperature difference between the two streams, which results in a difference in vapor pressure that leads to the transfer of the produced vapor through the membrane to the condensation surface.

Today MD is currently used in industrial process for liquid treatment [88], brine post-treatment (see section 2.4) and water desalination. The unit size usually ranges between 0.15-15 $^{m^3}/_{day}$; hence, it is suitable for medium-small application. Desalination plant based on solar driven MD are not yet fully commercially available. However, this technology is expected to reach the commercial state in the near future.

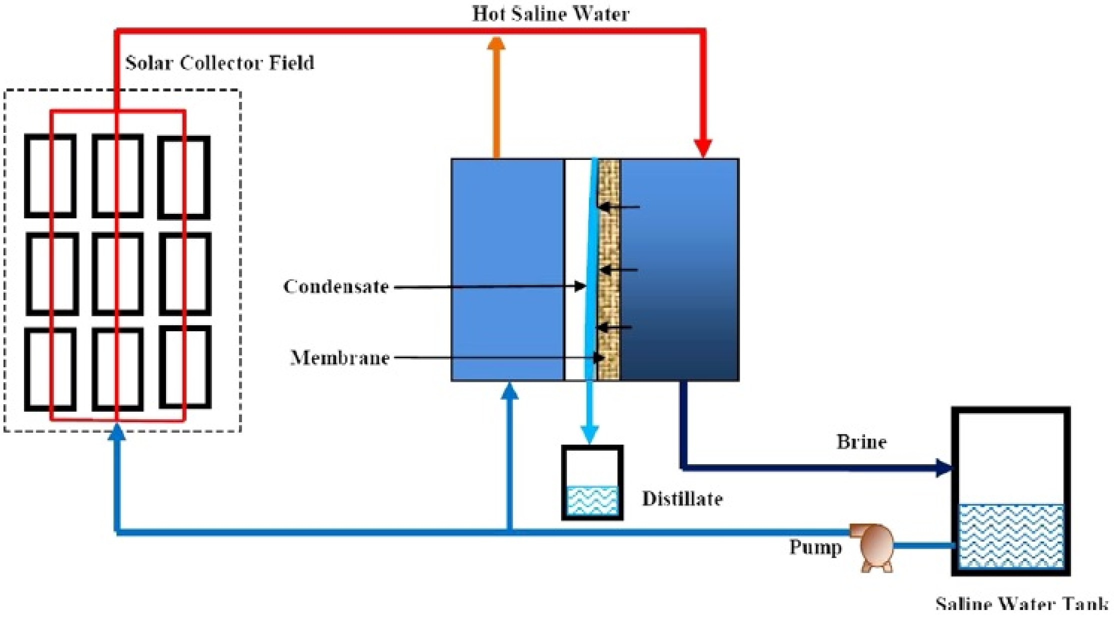


Figure 2.18: Schematic layout of an MD desalination system [89]

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[3] i.e hydrophobic membrane

2.2.3.2 The MD process

As shown is figure 2.18, the salt water is first driven by a pump partially to a solar collector field and partially to the left side of the distillation vessel. Hence, the two flows get heated, due to the solar radiation and to the latent heat of condensation of the distillate respectively. After that, the two flows get mixed, and pass through the right side of the distillation vessel. Due to the temperature of the feed water flow (80°C), a small part becomes vapor. Only the vapor molecules are allowed to pass through the membrane, due to the characteristic of the membrane itself. Hence, the vapor molecules cross the membrane, thus reaching the left side of the distillation vessel, which is at a lower temperature. Therefore, the condensation occurs because of the difference of temperatures. The condensing vapor eventually becomes the distillate, whereas the not-evaporated feed flow becomes the brine to be discharged.

The heat and mass transfers occurring in the membrane are the most important process of the system; hence, the following paragraphs describe the different layouts developed to foster them.

Direct contact membrane distillation (DCMD) In the DCMD configuration, the feed hot solution is in direct contact with the hot-membrane-side surface (see figure 2.19). Therefore, evaporation takes place at the feed-membrane surface. The vapor is moved by the pressure difference across the membrane to the permeate side and condenses inside the membrane module. Because of its hydrophobic characteristic, the feed cannot penetrate the membrane (only the gas phase is able to cross the membrane pores). DCMD is the simplest MD configuration and it is mainly employed in desalination processes. The main drawback of the current layout is the heat lost through conduction [88].

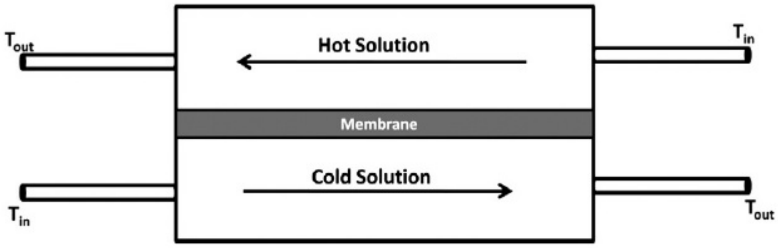

Figure 2.19: Schematic layout of a direct contact MD

Air gap membrane distillation The schematic layout of the Air Gap Membrane Distillation (AGMD) is shown in figure 2.20. The feed solution is in direct contact with the hot side of the membrane surface only. Stagnant air is introduced between the membrane and the condensation surface. The vapor crosses the air gap and then condenses over the cold surface inside the membrane cell, thus reducing the conductivity heat loss. However, the presence of stagnant air introduces a resistance to the mass transfer, which reduces the distillate production. This configuration is suitable for desalination and removing volatile compounds from aqueous solutions.

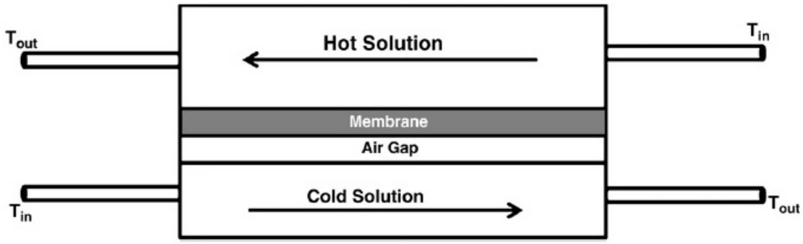

Figure 2.20: Schematic layout of an air gap MD

It is worthwhile to remember other two layouts, the Sweeping Gas Membrane Distillation and the Vacuum Membrane Distillation. The first is an AGMD, employing a moving air layer, in order to reduce the mass transfer resistance. The latter instead employs a pump to create a vacuum in the permeate membrane side. Condensation takes place outside the membrane module so that the heat lost by conduction is negligible. Those two layouts are commonly used in industrial systems for removing volatile compounds from aqueous solution, and they are not usually employed for desalination purposes [88].

2.2.3.3 Techno-economical features

Although the MD technology is thermally driven, the production of fresh water is strongly linked to the membrane quality. Therefore, the two crucial elements of the MD process are the thermal efficiency, that can be measured through the GOR, and the quality of the membrane.

MD is a new technology that has recently attracted interest thanks to its peculiarities. The operating temperature ranges between 50°C and 90°C, lesser than other processes such as MSF (90-120°C) and HDH (100°C) [40]; hence, it is particularly suitable for low-grade heat, such as waste heat or solar thermal collector's heat. Moreover, it is very flexible and it is able to work intermittently without an energy storage. The membrane is less complex than the ones used by a RO unit (see subsection 2.3.1), and it does not need a chemical pretreatment; in addition the membrane is more resistant to fouling and scaling [52]. Thanks to the simplicity of the membranes, the absence of moving parts and the low-cost materials required for the construction, MD is expected to be a appropriate and affordable technology for rural areas [88].

Despite its high potential, MD technology it is not fully commercialized, and only some pilot-scale projects have been already implemented [90, 91]. Further studies on the membranes and on the behavior of this system in real-life condition are needed to identify the actual potential of this technology [39, 44, 92]. A very interesting example of an integrated renewable system based on MD and designed for rural areas application is reported by Achmad Chafidz et al [93]. Therefore, it is not possible to define a range for MD's WPC, SWP and GOR, not even a very wide one [94].

Although MD is not fully developed, due to the great interest of the scientific community, the already-carried-out research of the past ten years, and the peculiarities that makes it appropriate for rural areas, it was decided to include this technology in the current study. As a matter of facts, in the next 10–20 years it is expected to see a massive increase of production capacity of MD technology [94].

2.3 Membrane desalination

The main membrane processes are Reverse Osmosis (RO) and Elecrodialysis (ED). In a membrane process, fresh water is produced from salt water by allowing passage of water molecules (in case of RO) or ions (in case of ED) through membranes by applying high pressure or electrical potential. The salinity of feed water plays an important role in determining the yield and the energy requirement of the unit.

Forward osmosis (FO) is currently considered a promising third membrane desalination technology. FO takes advantage of naturally induced water diffusion across a semi-permeable membrane from a low concentration solution to a high concentration solution, called draw solution. For water reuse and desalination, FO requires very little energy. However, the permeate of FO is not a product water ready for consumption but a mixture of drawn water and draw solution. As a result, a second step of separation must be employed to produce clean water and to regenerate the draw solution. Since it is at the first stage of technology development, far from commercialization in the small-scale desalination market, FO is not included in the study.

2.3.1 Reverse Osmosis

2.3.1.1 Overview

Reverse osmosis is the main membrane process used in water desalination. Osmosis is a natural process in which, when a dilute solution is separated from a concentrated solution by a semi-permeable membrane, the pure solvent flows from the dilute solution to the concentrated one through the membrane under the osmotic pressure gradient. This flow of water continues until the osmotic pressures of the two solutions reaches osmotic equilibrium. If an external pressure - greater than the osmotic pressure difference - is applied on the concentrated solution side then the solvent flow is reversed.

This process is known as reverse osmosis (RO) and it is advantageously used to remove water from the concentrated solution.

RO is a mature technology and it is known to be the most economical process available today because of recent developments in the technology and lower energy requirements compared to thermal processes. Due to its modular nature, this process is appropriate for all plant capacities: its installed capacity ranges between 0.1 m^3/day (used in marine and household applications) to 395,000 m^3/day (for commercial applications) [44].

The convenience of RO for desalinating small quantities of water for remote and isolated areas - thanks to the low energy consumption and the little need for maintenance - makes the process suitable for the coupling with renewable energy technologies, especially wind turbines and photovoltaic panels.

2.3.1.2 The RO process

As it is shown in figure 2.21, the RO process is made up by four subsystems: (1) pretreatment, (2) high-pressure pump, (3) membrane and (4) post treatment. An energy recovery system is often used in order to decrease the energy requirement of the process and it can be considered as the possible fifth subsystem.

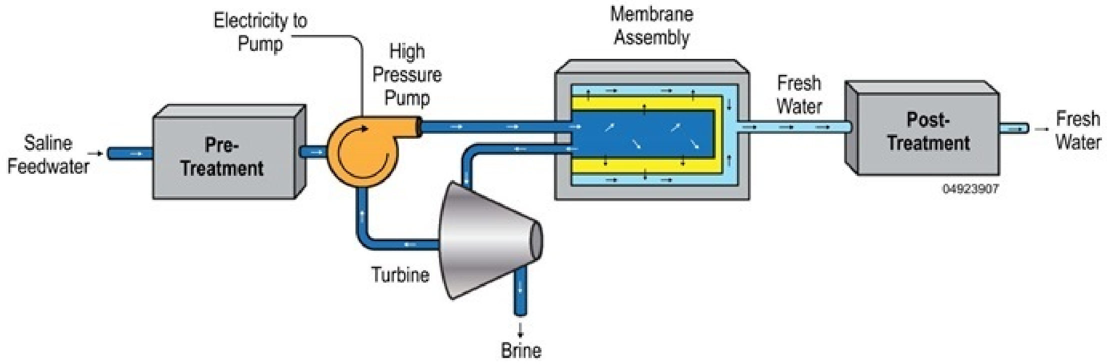

Figure 2.21: Schematic layout of a RO unit [44]

Pretreatment

Feed water must be treated to protect the membranes and to facilitate membrane operation. The pretreatment involves filtration, sterilization and addition of chemicals.

Membrane fouling is caused by particles and colloidal material which are present in the feed water and are concentrated on the membrane surface. A RO system must operate within a frame of operating conditions to minimize the fouling rate.

Hence, suspended solids are removed by filtration, pH adjustments are made to protect the membrane and control precipitation of salts and antiscaling inhibitors are added to control calcium carbonates and sulfates. A disinfectant is added to control biofouling of the membrane. Marine organisms, algae and bacteria must be also eliminated, and if ozone or chlorine are used they should be neutralized prior to contact with the membrane.

Continuous raw water pretreatment increases the lifespan of the membrane but it also requires maintenance of the RO unit to replace regularly certain chemicals.

Typical separation processes as nano-filtration, ultra-filtration and micro-filtration are recently used in the pretreatment stages of desalination to remove ions, bacteria, large particles and for water softening. Most of the new plants are using membrane softening instead of chemical softening because it allows using lesser amounts of chemicals, which is more environmentally friendly and results in a great reduction in replacement costs. In the current study, these processes will not be analyzed; for further information see [36, 40, 43, 47, 95].

High pressure pump

The high-pressure pump generates the pressure needed to force the water to pass through the membrane; therefore, the energy needed to drive the pumps is electricity. The energy requirement of a RO high pressure pump is analyzed in paragraph 2.3.1.3.

The reverse osmosis unit can operate between its nominal load, P_D, and a minimum load, P_{MD}, because of membrane's characteristic curve:

$$P_{MD} \leq P_{DES} \leq P_D$$

where: P_{DES} is the instant power consumed by the desalination unit. The lower operation limit P_{MD} corresponds to the minimum required pressure to overcome the osmotic pressure and to set desalination unit up (typically around 17/20 bar). On the other hand, the pressure must be kept below the membrane tolerance pressure P_D, typically around 80 bar.

Hence, the operating pressure of a RO unit usually ranges from 17 to 27 bars for brackish water and from 55 to 82 bars for seawater [44, 92, 95, 96].

Membrane

The membranes are designed to yield a permeate water of about 500 ppm, that is the limit value set by the World Health Organization (WHO) for fresh water [3].

Common membranes are polymeric materials such as cellulose triacetate or polyamides and polysulfones. Selection factors for membranes include working life, pH stability, pressurization capacity, mechanical strength and selectivity for solutes. Membranes are located in a module and they can be used in four alternative configurations, namely tubular, flat plate, spiral-wound and hollow fiber. Each has its own characteristics that affect selection in particular cases. Hollow fiber and spiral configurations generally have more favorable operating characteristics of performance relative to cost and they are most commonly used. In figure 2.22, schematic drawings of both a hollow fiber and a spiral-wound module are reported.

In a modern RO plant the membranes can work properly up to 10 years and they are grouped together in modules which are linked together in series or parallel configurations, according to the size of plant required and to desired recovery ratio [97].

Recovery ratio As the feed water enters the RO system, only part of the water comes out as treated water. Part of the water fed into the system is used to wash away the rejected compounds and goes down the drain as waste. If not properly designed, only little amount of treated water will be obtained from large quantities of water fed to the RO systems. As it was introduced in section 2.2 for thermal desalination processes, the recovery ratio, or efficiency, of the RO system can be calculated by dividing the volume of treated water produced by the volume of water fed into the system:

$$\%\,Recovery = \alpha = \frac{Volume\,of\,treated\,water\,produced}{Volume\,of\,feed\,water\,used}$$

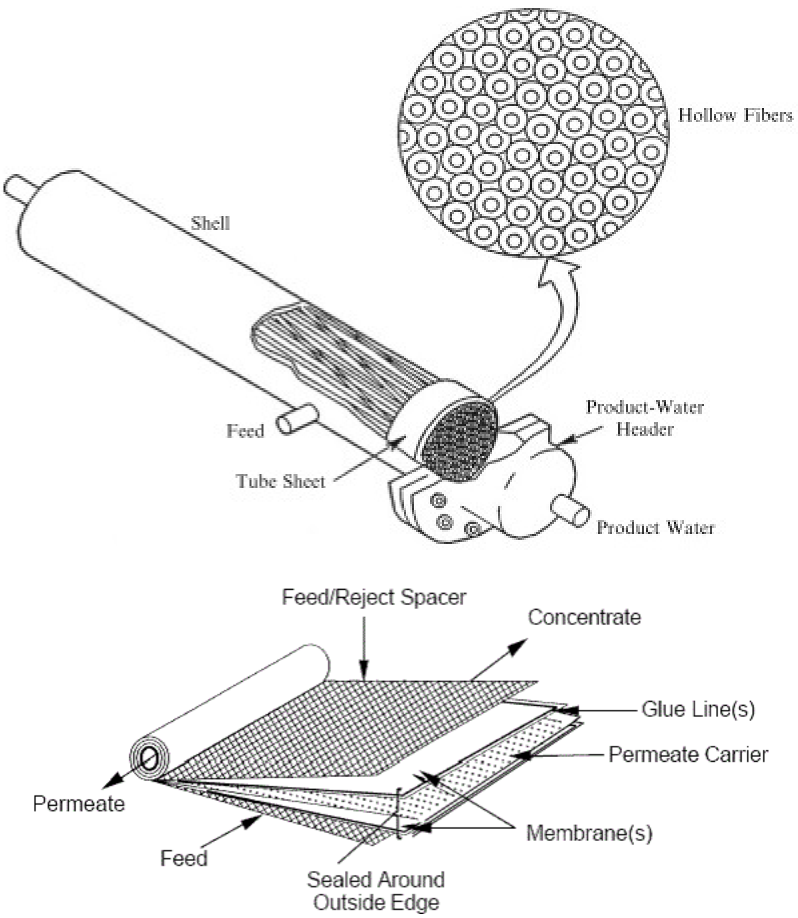

Figure 2.22: Schematic drawings of a hollow fiber and of a spiral-wound module [95]

If the recovery ratio is increased when water pressure is left constant, the salts in the residual feed become more concentrated and the natural osmotic pressure will increase until it is as high as the applied feed pressure. The maximum recovery rate usually depends on the limiting osmotic pressure, the concentration of salts present in the feed water and the tendency of salts to precipitate on the membrane.

The recovery ratio increased considerably over the years due to improved salt rejection of the membranes. The recovery ratio for normal seawater desalination (35,000 ppm of salinity) was about 25% in 1980s and it increased to 35% in 1990s. Brackish water RO plants can typically recover 50–80% of the feed water, with 90–98% of salt rejection. For seawater, recovery rates vary from 30 to 40%, with 90–98% of salt rejection, and it can reach 60% if a second stage is applied [43, 92, 95].

Post treatment

Fresh water from the membrane module is not yet safe to be consumed. After passing through membrane module, fresh water needs to be stabilized before it is ready to be consumed. In post-treatment, pH of fresh water is adjusted to approximately 8, and addition of corrosion inhibitors like polyphosphates may be necessary.

The rejected water may pass through the energy recovery system if implemented. In any case, it needs to be processed before being released into environment. Reject water which has high salinity would damage the ecosystem of its surroundings, especially for brackish water where there is no option to dilute the reject water before disposing (see section 2.4).

2.3.1.3 Energy consumption in RO process

Electricity is the only required form of energy in the RO process. Energy consumption of the RO unit depends mainly on the salinity of the feed water and the recovery rate.

Whereas the percentage of TDS in seawater has practically no effect in thermal processes, in a RO process higher water salinity requires more energy to overcome the osmotic pressure. In particular, the energy demand increases linearly at a rate of more than 1 kWh/m^3 per 10,000 ppm [40].

There has been much progress over the past decade in advancing the development of new emerging water desalination technologies that could significantly lower the specific energy consumption compared to the present conventional processes.

Table 2.3 summarizes the energy requirement of medium/small-scale RO plants reported in experimental, modeling and review studies, retrievable in the scientific literature in the last decade[4].

As a baseline, a seawater reverse osmosis (SWRO) process can reach a specific energy consumption of 2-4 kWh/m^3 with the aid of an energy recovery system. The average reported energy consumption of an SWRO ranges from 3 to 10 kWh/m^3.

Low pressure is needed to desalinate brackish water; therefore, different membranes are used and much higher recovery ratios are possible, which makes energy consumption low. For a brackish-water RO (BWRO) unit, the electrical energy consumption ranges typically from 1 to 3 kWh/m^3.

Energy recovery system

As previously mentioned, RO desalination, in particular SWRO, is an energy intensive process. Therefore, it is important to make use of energy saving methodologies.

Energy saving methodologies are employed mainly to recover the energy carried over by the brine leaving the RO system at high pressure. For example, in a seawater RO plant operating at 55-69 bar with a recovery ratio of 15-40%, the brine leaves the RO modules at

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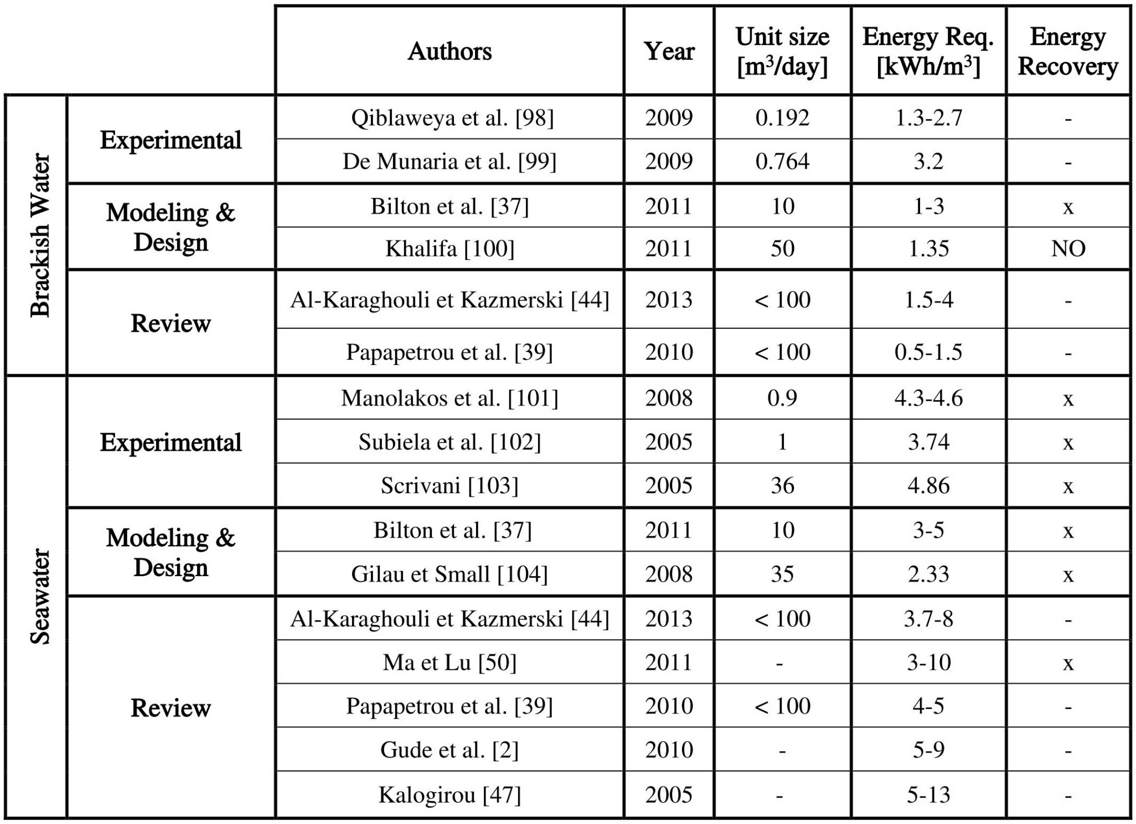
[4] from 2005 to 2014



		Authors	Year	Unit size [m^3/day]	Energy Req. [kWh/m^3]	Energy Recovery
Brackish Water	**Experimental**	Qiblaweya et al. [98]	2009	0.192	1.3-2.7	-
		De Munaria et al. [99]	2009	0.764	3.2	-
	Modeling & Design	Bilton et al. [37]	2011	10	1-3	x
		Khalifa [100]	2011	50	1.35	NO
	Review	Al-Karaghouli et Kazmerski [44]	2013	< 100	1.5-4	-
		Papapetrou et al. [39]	2010	< 100	0.5-1.5	-
Seawater	**Experimental**	Manolakos et al. [101]	2008	0.9	4.3-4.6	x
		Subiela et al. [102]	2005	1	3.74	x
		Scrivani [103]	2005	36	4.86	x
	Modeling & Design	Bilton et al. [37]	2011	10	3-5	x
		Gilau et Small [104]	2008	35	2.33	x
	Review	Al-Karaghouli et Kazmerski [44]	2013	< 100	3.7-8	-
		Ma et Lu [50]	2011	-	3-10	x
		Papapetrou et al. [39]	2010	< 100	4-5	-
		Gude et al. [2]	2010	-	5-9	-
		Kalogirou [47]	2005	-	5-13	-

Table 2.3: Energy consumption of a RO plant

a pressure of 51-65 bar. A major part of the hydraulic energy of the brine can be recovered converting the brine stream to power, employing an energy recovery system. Several studies state that the potential saving of the energy required by a SWRO system lies between 40 and 60% [38, 43, 95, 97, 105].

The energy is recovered from the brine side of the process through either turbo or volumetric system. The former – usually called energy recovery turbine (ERT) - converts the hydraulic energy in the reject stream into rotational energy, in the form of mechanical shaft power, by an energy recovery turbine. It includes reversible pumps, Pelton turbines, turbochargers and a hydraulic pressure booster. The efficiency of centrifugal ERT is typically in the range of 80–88% in converting hydraulic energy into rotational mechanical power that is converted back to hydraulic energy.

The second approach for energy recovery implies the use of positive displacement systems such as ERI pressure exchanger, DWEER (Dual Work Exchanger), or the KSB device. These systems use the principle of positive displacement to transfer the energy contained in the reject stream directly into a new stream. Positive displacement pumps typically offer lower flow rate and higher discharge pressure capabilities than centrifugal pumps. The efficiency of all these devices can be quantified as the ratio between the entering and the exiting hydraulic energy. Most of these devices achieve relatively-similar net energy transfer efficiencies between 91 and 96%. The energy saving is achieved by reducing the volumetric output of the high-pressure pump [43, 95].

Since the unit cost of the electricity produced from renewable energy systems is high, the implementation of an energy recovery system on a renewable-powered RO plant constitutes a great opportunity for a substantial cost reduction as it allows both the reduction of the size of the high-pressure pump and the size of the energy system. De facto, the advent of efficient and reliable energy recovery systems has greatly enhanced the compatibility of RO with solar photovoltaic systems and other renewable energy forms.

Recovery ratio and energy consumption

Low recovery systems consume less energy in the separation process but consume more in pumping; therefore, there is an optimized range for the seawater recovery. The work required by an RO unit with an energy recovery device may be estimated by:

$$W_{SWRO}\,[kJ] = \frac{V_{fresh}}{\eta_{pump}} * \left(\frac{P_{sea}}{1-\alpha} + \triangle P\right) * \left[1 + \left(\frac{1}{\alpha} - 1\right) * (1 - \eta_{ERD})\right]$$

where α is the seawater desalination system recovery ratio, ΔP is the transmembrane pressure difference; P_{sea} is the osmotic pressure given by van't Hoff equation: $P_{sea} = cRT$ where c is the ionic molar concentration, R is the universal gas constant and T is the operating temperature of RO unit; and $\frac{P_{sea}}{1-\alpha}$ is the pressure used to overcome the concentrated brine osmotic pressure. η_{pump} is the high pressure pump efficiency, V_{fresh} is the fresh water volume and $\frac{V_{fresh}}{\alpha}$ is the total seawater pumped by the pump, and η_{ERD} is the efficiency of the energy recovery device.

For detailed analysis of the basic relations that lead the process, see specific studies as [92, 95].

2.3.1.4 Energy solutions for rural RO desalination

Several opportunities to satisfy the electric requirement of a small-scale RO plant exist for rural areas. Table 2.4 reviews several studies of the last two decades[5] in which are presented various possible small-scale combinations of both simple systems and hybrid configurations, which combine different simple systems.

Several studies on sustainable desalination technologies for rural areas evaluate and compare the implementation of diesel-RO systems with renewable-powered RO plants (see table 2.4). Hence, the main features of a diesel generator pointed out in subsection 1.2.1 must be considered. In particular, diesel-powered RO systems are interesting solutions because of their

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[5] from 2001 to 2014

	Authors	Simple without Batteries			Simple with Batteries		Hybrid		
		PV-RO	*W/G-RO*	*Diesel-RO*	*PV-Batt-RO*	*W/G-Batt-RO*	*PV-W/G-Batt-RO*	*W/G-Diesel-RO*	*PV-W/G-Diesel-RO*
Experimental	Al Suleimani et Nair [106]	x		x					
	Manolakos et al. [101]	x			x				
	Mohamed et al. [107]				x				
	Carvalho et al. [108]				x				
	Herold et al. [109]				x				
	Espino et al. [110]				x				
	Koklas et Papathanassiou [111]					x			
Modeling & Design	Bilton et al. [37]	x		x					
	Laborde et al. [112]	x							
	Mohamed et Papadakis [105]	x					x		
	Koutroulis et Kolokotsa [6]				x	x	x		
	Gilau et Small [104]	x		x	x	x	x	x	x
	Bourouni et al. [41]	x	x				x		
	Khalifa [100]			x	x	x	x		x
Review	Al-Karaghouli et Kazmerski [44]	x	x		x	x			
	Papapetrou et al. [39]				x	x			
	Gude et al. [2]			x	x	x			
	Al-Karaghouli et al. [113]				x	x			x

Table 2.4: Energy solution for rural RO systems

low capital cost and their flexibility that allows a RO plant to work 24-hours and to have higher water daily production rates than any renewable-powered desalination plant.

Only stand-alone systems are considered in the current study and in table 2.4, since it is hypothesized that the target rural areas have no access to the electric grid.

Moreover, only PV-RO is presented as solar-driven RO opportunity since solar thermal assisted RO is still far from commercialization. For more detail information on solar-thermal RO systems, see [89] and [92].

Photovoltaic-driven RO (PV-RO)

PV-powered reverse osmosis is considered one of the most-promising forms of renewable-powered desalination especially when used in remote areas for medium/small-scale applications, because both PV and RO are modular and easily scalable. Hence, small-scale PV-RO has received much attention in recent years and numerous systems have been implemented (see table 2.4).

In a PV-RO unit, the power required for the desalination process is supplied by photovoltaic panels; the system includes a DC inverter and it can be operated with or without batteries (see figure 2.23).

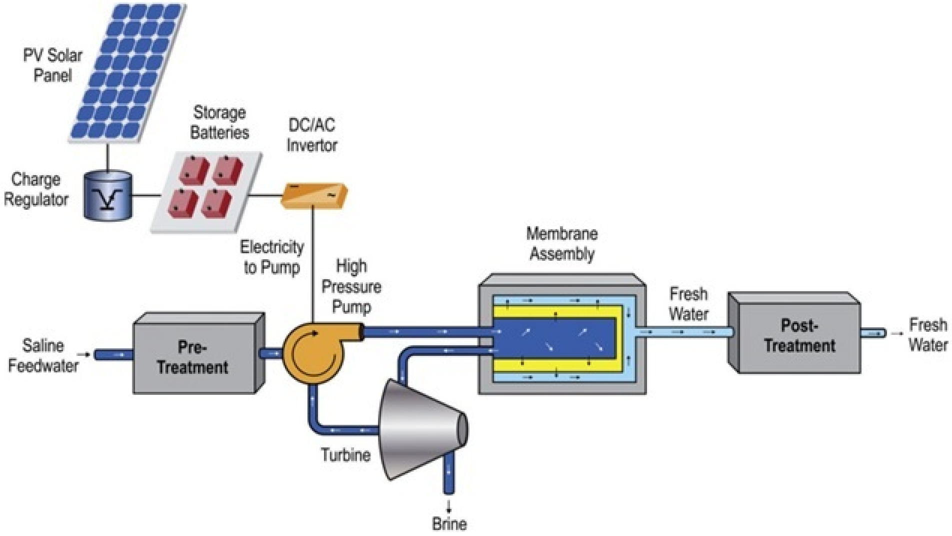


Figure 2.23: Schematic layout of a PV-RO unit [44]

As already stated, the compatibility of RO with solar PV power and other renewable energy forms has been greatly enhanced by the advent of efficient and reliable energy recovery pumps, which recycle the hydraulic energy of the reject brine to assist pumping of the feed water.

Generally speaking, a PV-RO combination works like two independent units of PV and RO. Parallel to the advantages of RO technology, the use of photovoltaic cells as a source of power is an excellent choice in rural areas due to:

- Modularity, that makes the system easily scalable and avails system enlargement whenever needed.
- Low maintenance, that means reduced operation and maintenance costs especially in the case of battery-less systems. Particular attention must be given to the dust and sand settlements on the panels: the resulting energy-yield losses and permanent degradation of the PV cells are a critical problem in arid rural areas.
- Efficiency of the system, that is maintained more or less constant throughout its life.
- Long life. Currently, solar panels are guaranteed to stay in service up to 20 years, and withstand harsh environments.
- Well-matched to load, as solar panels produce more energy in areas of higher solar irradiation where the people are likely to consume more drinking water.
- Environmentally friendly, since PV energy has no emission of pollutants and low noise level, since PV panels have no rotating parts.

The huge ground area normally required for solar panels, especially when the power demand is high, represents a limiting factor which negatively affects their widespread use.

Nevertheless, the main limitation in using PV technology for water desalination is the high cost of PV cells. However, the cost of PV cells is experiencing significant reduction in the last years. Ghaffour et al. [40] state that according to a new report published by GTM Research, production costs for PV cell industry will fall from 50 cents per watt in the fourth quarter of 2012 to 36 cents per watt by the end of 2017. The report predicts that the majority of these cost declines will derive from technology innovations such as diamond wire sawing for PV wafers, advanced metallization solutions, and increased automation in place of manual labor.

The total lifetime costs of PV-RO plants vary substantially by location due to variations in solar resources, water salinity, system demands and local governmental policies.

Moreover, high ambient temperatures that exist in the Middle East degrade the performance of photovoltaic panels: the performance of crystalline silicon solar cells with increasing temperature drops by about 0.4% per °C. This factor should be taken into account when sizing a solar array to keep powering the connected system throughout its lifetime.

A more serious problem usually encountered when using solar panels for powering desalination units in remote areas is the need for a backup system both to enable powering the desalination unit by night and during blackout hours and to offer stable power to the RO unit. As a matter of fact, a RO system has to cope with the sensitivity of the membranes regarding fouling, scaling, as well as unpredictable phenomena due to start-stop cycles and partial load operation during periods of oscillating power supply. Hence, an array of batteries is often integrate in the system. Rechargeable batteries used to store the produced electricity require high capital cost and periodic maintenance. Several problems are encountered using batteries: premature battery failure, leaks in the lead-acid batteries and battery efficiency. Typical battery lifetime in Europe is between 3 and 8 years, but in hot countries it is reduced to 2-6 years due to internal corrosion at high temperatures. The battery efficiency in the market is about 75–80%. This indicates that around 20–25% larger PV array area is required [2, 114].

A solution to minimize the battery storage is to integrate a water tank into the system. Water is an excellent storage medium and can be stored in vast quantities for extended periods of time. Therefore, it is possible to produce water and store it when the power supply is available, and use it when the power supply drops, thus alleviating the need for expensive back-up systems.

A third alternative of backup system is to install a hybrid diesel–solar powering system where the RO unit is driven by a diesel generator by night or during cloudy days (see paragraph Hybrid RO).

Wind-driven RO (W/G-RO)

Electrical or mechanical power generated by a wind generator (W/G) is an excellent candidate for powering a RO unit, especially in remote areas with appropriate wind conditions. W/G desalination systems, in particular W/G-RO systems, are one of the most frequent renewable desalination plants, especially for coastal areas and islands presenting a high availability of wind energy resources. The majority of the implemented W/G-RO units were installed in the 90's and their typical capacity ranged from 50 to 2,000 m^3/day. In particular, significant applications had been implemented in the Greek Aegean Islands and in the Spanish Canary Islands [2, 39, 41, 44, 50].

The design of the control system is the most critical step in the design of a desalination RO unit powered by a W/G. The fluctuation of wind speed requires a control system that matches the available wind power to the electricity requirement of the desalination unit and dumps the extra wind energy resulting from very high speed to achieve a stable operation, since the power variations have an adverse effect on the performance and component life of certain desalination equipment. Hence, a battery system – costly, inefficient and short-living, as already stated - is normally integrated to smooth the operation.

Despite the difficulty to scale the W/G to small-size applications and to design a proper control system, the prospects of the W/G-RO combination are promising, mainly due to the low cost of wind energy. Hence, an alternative to the battery system has been developed to smooth the operation: to integrate wind energy with other energy sources either conventional or renewable, such as solar PV or thermal, diesel, etc. Hybrid systems of PV-W/G has been successfully implemented in remote areas (see paragraph Hybrid RO).

Hybrid RO

Photovoltaic energy and wind generator combination (PV-W/G) is another interesting RES-RO configuration, since it has a greater flexibility compared to the previous configurations (see figure 2.24).

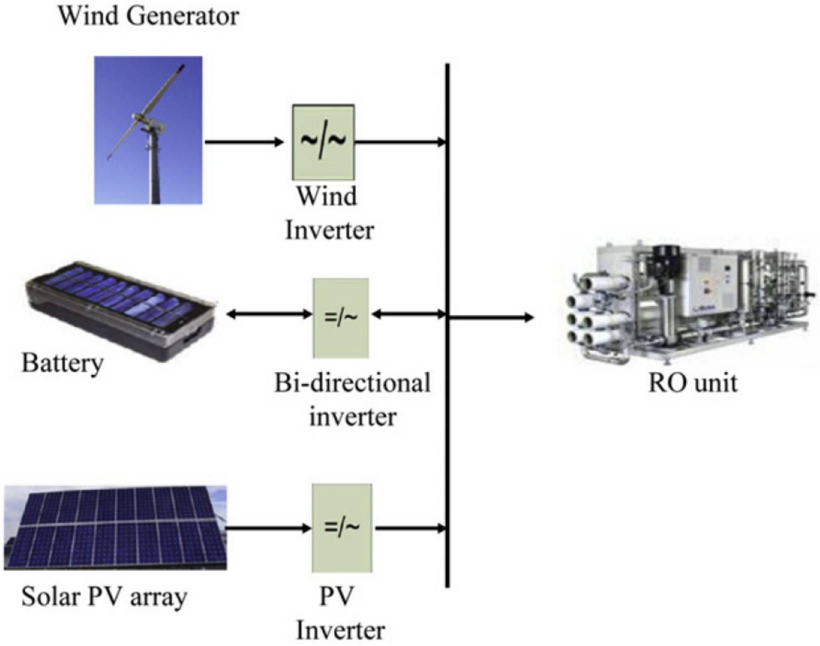


Figure 2.24: Schematic layout of a hybrid RES-powered RO system [6]

The first study on a demonstration project of a PV-W/G-RO system hailed from 1979, when Petersen et al. reported the performances of two RO desalination plants supplied by a 6 kW wind energy converter and a 2.5 kW solar generator for remote areas [115]. Several design studies and installations of hybrid PV-W/G-RO systems are reported on the scientific literature in the last ten years [see table 2.4].

Among others, a design optimization study by Koutroulis and Kolokotsa [6] compares different energy system solutions for a desalination system of about 11 m^3/day. The results show that using the hybrid PV–W/G configuration results in lower overall costs compared to desalination systems power-supplied by either PV or W/G sources exclusively. This result is due to the considerably higher number of PV modules and PV battery chargers required to implement the only-PV system and the increased number of W/Gs and batteries needed to cover the power demand for the only-W/G system, under the specific region's solar radiation and wind speed conditions. Other studies report similar results [38, 100, 105].

As well as for the PV-RO and the W/G-RO systems, the maintenance of the battery bank system can be a major concern also for the hybrid one. Hence, the implementation of a water tank has to be considered.

A diesel generator can represent a good alternative to battery storage as a back-up system. With an appropriate design, combining a reliable diesel generator with one or more RES generators can solve several of the mentioned economic and environmental problems to supply the energy demands in a sustainable way in the particular context of the rural areas (see figure 2.25).

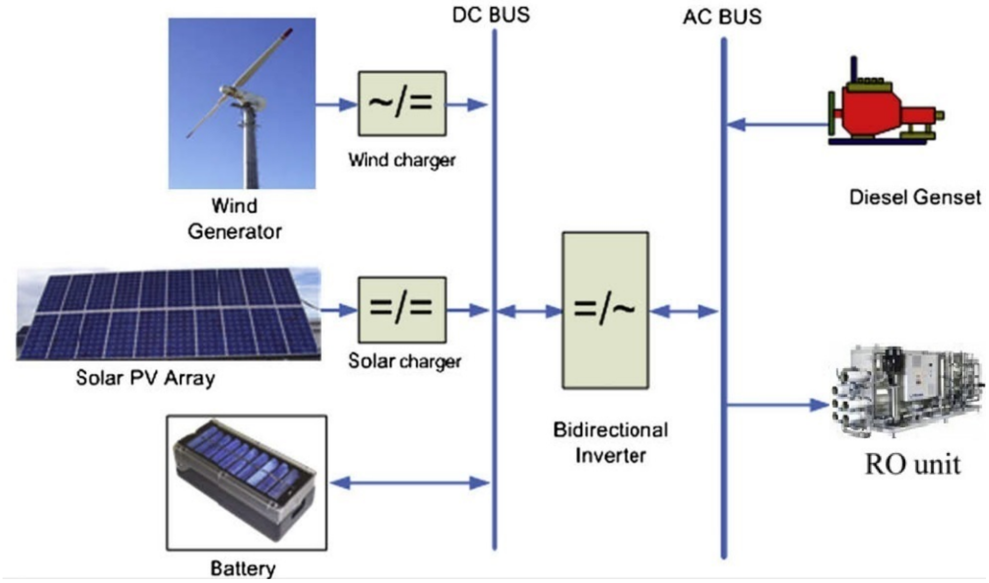


Figure 2.25: Schematic layout of a hybrid-powered system [116]

De facto, a hybrid power system has the ability to provide electricity to the load 24-hours. This system offers better efficiency, flexibility of planning and environmental benefits compared to the diesel generator stand-alone system. The usual maintenance costs of a diesel generator can be decreased as a consequence of improving the efficiency of operation and reducing the operational time, which also means less fuel usage. Furthermore, the system provides an opportunity for expanding its capacity in order to cope with increasing demand in the future, boosting either the rated power of the diesel generator, renewable generator or both.

Several researches study the implications of a diesel-RES hybrid-RO (PV-Diesel-RO; W/G-Diesel RO and/or PV-W/G-RO) in terms of capital cost, water production costs (WPC), fuel consumption and pollutants emission (see table 2.4).

2.3.1.5 Economics

There have been many developments over the last three decades that have contributed to a reduction in WPC of RO desalination, particularly – as already mentioned - membranes performance and costs decrease and reduction in energy consumption caused by more efficient energy recovery systems. The other important improvements in RO technology are:

- Improvements in pretreatment processes (including nano-filtration, ultra-filtration and micro-filtration). Most of the new plants use amounts of chemicals with a great reduction in consumable costs.
- Improvements in design with use of different configurations and improvements in linking processes.
- Development of a high boron rejection membranes that produce an acceptable concentration in the permeate without requiring a second pass RO system.
- Reduction in usage of chemicals with improved membrane performance. Injection of acid and antiscalant is not always necessary.

Table 2.5 compares each different power scenario on different economical and technical parameters of performance. The comparison is based on a critical review of the literature reported in table 2.4.

		WPC [$/m^3]	**Capital Cost**	**O&M and replacements**
Diesel RO	Brackish water	1 - 4	Low	- High fuel consumption - Generator replacement after 10 years - Daily maintenance needed
	Seawater	1 - 5		
PV-RO	Brackish water	2 - 7	High	- No fuel consumption - Battery replacement after 5 years - Little maintenance
	Seawater	4 - 11		
W/G RO	Brackish water	2 - 4	Medium-High	- No fuel consumption - Battery replacement after 5 years - Little maintenance needed
	Seawater	4 - 7		
Hybrid RO	Brackish water / Seawater	2 - 5	Medium	- Low fuel consumption - No replacement needed - Frequent maintenance needed

Table 2.5: Economics of rural RO systems

Generally, the WPC of a diesel generator tends to be lower than in any other renewable solution (1-5 $\$/m^3$), since the introduction of a renewable energy source increases the capital cost.

The difference, however, may be compensated by the advantages of introducing renewable energy systems such as eliminating the need for fuel transportation and routine maintenance to the diesel generator. Moreover, the contribution on the WPC of both the cost of fuel transportation and the cost of maintenance is deeply affected by the peculiarities of the specific rural area: location, existence of proper communication routes, presence of manpower, etc. Hence, in some locations with abundant renewable sources the WPC of a RES-RO unit can be lower than the diesel-RO one.

As already mentioned, the different hybrid configurations are intermediate solutions that allow to have less operating costs than a diesel-RO unit and less capital cost than PV-RO and W/G-RO units.

2.3.1.6 Final considerations

Reverse osmosis technology is becoming more popular because of the following advantages:

- The specific energy requirement is significantly low.
- The modular structure of the RO process increases flexibility in building desalination plants within a wide range of capacities, preventing an excessive increase of investment costs at low capacities.
- The process is electrically driven. As a result, it is readily adaptable to be powered by PV panels and wind turbines.
- The RO plant is normally operated at ambient temperature, which reduces the headache of scale formation and corrosion problems, especially when the pretreatment system is properly designed and kept under control.
- Other advantages of RO systems include: ease of operation, flexibility in capacity expansion and short construction periods.

The advantages of using renewable energy sources for generating power in remote areas are manifest: the cost of transported fuel is often prohibitive, and there is increasing concern about fossil fuels and the issues of climate change and global warming. Hence, the potential combination of PV power with RO has generated growing interest because of inherent simplicity and elegance of both technologies. Moreover, the prospects of the wind-RO combination are also promising, mainly due to the low cost of wind energy and to presence of high availability of wind power resources in coastal areas and islands.

The disadvantages of stand-alone power systems using renewable energy is the high capital cost and that the availability of renewable energy sources has daily and seasonal patterns which result in difficulties in regulating the output power to cope with the load demand. Hence, combining renewable energy generation with conventional diesel power generation is a viable solution that will enable the power generated from renewable energy sources to be more reliable and affordable.

The main drawbacks of renewable-powered RO units are the need of a significant pretreatment, the short-life time of the membranes and the high capital cost of the energy system.

2.3.2 Electrodialysis

2.3.2.1 Overview

Electrodialysis (ED) is an electro-membrane process for separation of ions across charged membranes from one solution to another under the influence of an electrical potential difference used as driving force. ED processes are different from the MSF, MED and RO systems in that dissolved salts are moved away from the feed seawater rather than the reverse.

ED was first commercially used in 1953 at an oilfield campsite in Saudi Arabia. In these decades, the process has been widely used for the desalination of salt water (mainly brackish water), for treatment of industrial effluents, for recovery of useful materials from effluents and for salt production. An ED plant's typical capacity ranges from 1 to 145,000 m3/day.

From a technical point of view, ED as well as PV are mature and commercially available technologies at present time, even though ED is available mostly in medium/high-sized units. PV-powered ED systems have been proven to be valid options for desalination at remote sites and they have started to be commercialized in the last decade.

2.3.2.2 The ED process

Figure 2.26 shows the schematic diagram of an ED unit. An ED unit usually consists of the following components: pretreatment system, membrane stack, low-pressure circulation pump, direct-current power supply (rectifier or photovoltaic system) and post-treatment system.

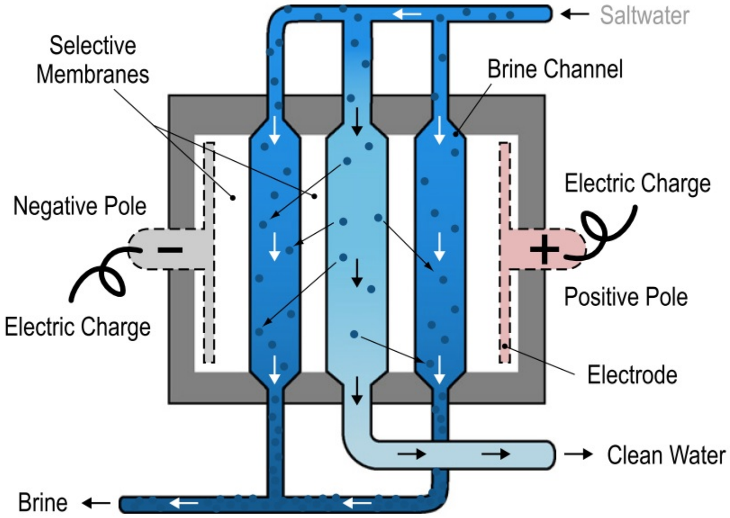


Figure 2.26: Schematic layout of an ED system [44]

Salt water contains ions. These ions are attracted to either positive or negative charges. The operational principle of ED takes advantage of this phenomenon as follows: electrodes are connected to an outside source of direct current (DC) in a container of salt water containing an ion-selective membrane connected in parallel to form channels. When salt water flows between these channels and electricity is charging the electrodes, positive salt ions travel through the cation-permeable membrane toward negative electrodes, and negative salt ions travel through the anion-permeable membrane to the positive electrode, which results in the removal of salinity from the water. As a result of this process, alternating channels are created: a concentrated channel for the brine and a diluted channel for the produced fresh water. Bacterial contaminants are not removed by the ED process itself, thus post-treatment is required for potable water use.

In an actual industrial ED process, a large number of alternating cation and anion membranes are stacked together, separated by plastic flow-spacers that allow the passage of water. The streams of alternating flow-spacers are a sequence of diluted and concentrated water which flow in parallel to each other.

The performance of ED in practical applications depends on membrane properties, feed solution composition and equipment design parameters such as the feed flow velocity, operation mode, the cell geometry and the spacer configuration in an electrodialysis stack. For detailed analysis of the basic relations that lead the process, see specific studies as [117, 118, 119, 120].

Electrodialysis reversed

In the early 1970s, an American company commercially introduced the electrodialysis reversed (EDR) process for electrodialysis [113]. EDR unit operates on the same general principle as a standard ED plant except that both the product and the brine channels are identical in construction.

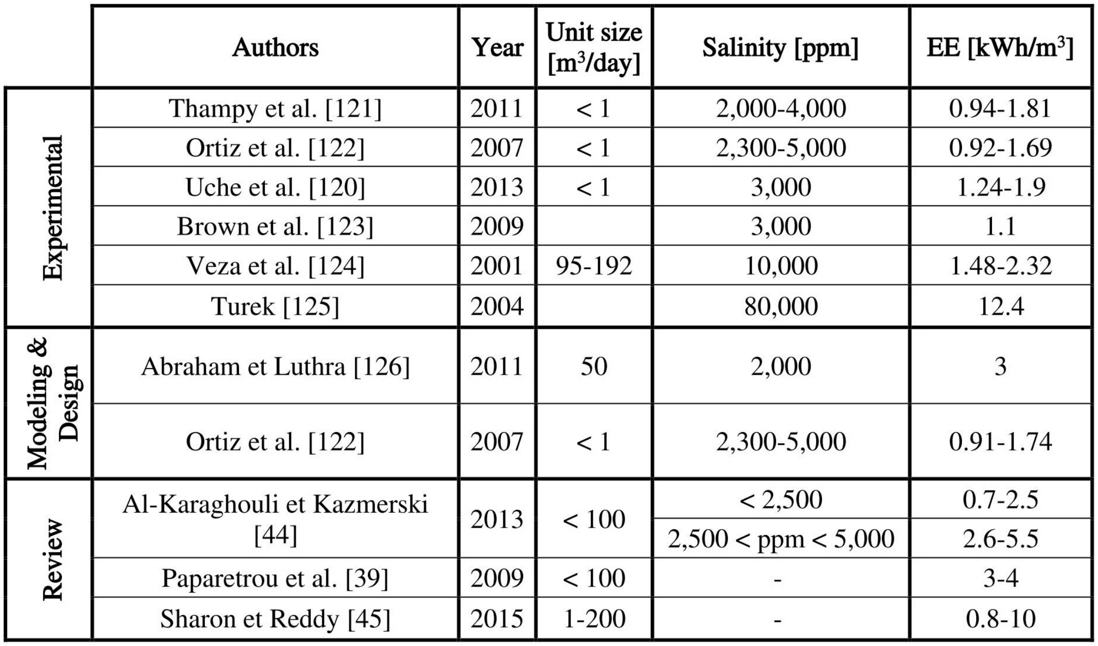
At intervals of several times an hour, the polarity of the electrodes is reversed and the flows are simultaneously switched so that the brine channel becomes the product-water channel, and the product-water channel becomes the brine channel. The result is that the ions are attracted in the opposite direction across the membrane stack. Immediately following the reversal of polarity and flow, enough of the product water is dumped until the stack and lines are flushed out, and the desired water quality is restored. This flush takes about 1 or 2 minutes and the unit can then resume producing water.

Reversing the flow increases the life of the electrodes and helps to clean the membranes driving salt scale off the membranes. The frequency and duration of field reversing depends on the turbidity and salt concentration of feed water. When the membranes are operated in the same direction all the time, precipitant can build up on the concentrate sides. On the other hand, EDR allows the unit to operate with fewer pretreatment chemicals and minimizes membrane fouling which is a major advantage of EDR over RO.

2.3.2.3 Energy consumption in ED process

Electricity is the only form of energy required for the ED process. DC electricity is used for ED electrodes, and AC or DC electricity is used to drive the pumps.

Table 2.6 summarizes the energy requirement of medium/small-scale ED plants reported in experimental, modeling and review studies, retrievable in the scientific literature of the last fifteen years [6]. In the ED process energy consumption is highly influenced by the salt concentration since it is proportional to salts removed and not to the treated volume: the higher is the saline concentration in the brackish water, the higher will be the electric consumption of the desalination process.



	Authors	Year	Unit size [m^3/day]	Salinity [ppm]	EE [kWh/m^3]
Experimental	Thampy et al. [121]	2011	< 1	2,000-4,000	0.94-1.81
	Ortiz et al. [122]	2007	< 1	2,300-5,000	0.92-1.69
	Uche et al. [120]	2013	< 1	3,000	1.24-1.9
	Brown et al. [123]	2009		3,000	1.1
	Veza et al. [124]	2001	95-192	10,000	1.48-2.32
	Turek [125]	2004		80,000	12.4
Modeling & Design	Abraham et Luthra [126]	2011	50	2,000	3
	Ortiz et al. [122]	2007	< 1	2,300-5,000	0.91-1.74
Review	Al-Karaghouli et Kazmerski [44]	2013	< 100	< 2,500	0.7-2.5
				2,500 < ppm < 5,000	2.6-5.5
	Paparetrou et al. [39]	2009	< 100	-	3-4
	Sharon et Reddy [45]	2015	1-200	-	0.8-10

Table 2.6: Energy consumption of a ED plant

For low salinity ($< 3{,}000$ ppm), the electrical energy consumption of an ED unit ranges typically from 0.7 to 2.5 kWh/m^3 (see table 2.6). For higher saline brackish water (3,000-10,000 ppm) and for seawater, the energy consumption increases remarkably. As a matter of fact, ED presents lesser energy efficiency than RO when feed water salinity is high and only few studies have been carried out on high salinity ED desalination so far [119, 127, 128], thus it is not possible to set a reasonable range of energy requirement for these applications.

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[6] 2000-2015

2.3.2.4 Energy solutions for rural ED desalination

As the process operates with DC power, in areas with abundant solar resource throughout the year, solar energy can be conveniently used with ED by directly producing the voltage difference required with photovoltaic (PV) panels.

Wind energy could be also used to power ED process, but most applications of coupling membrane processes with wind generators are wind-RO. Veza et al. [124] tested an ED desalination plant to treat brackish water while driven from an off-grid wind energy system, located in Gran Canaria Island (Spain). The unit included power converters for the membrane stacks and variable frequency drivers for the feed pumps. A number of tests were carried out showing good flexibility, adapting smoothly to variations in wind power, even when sudden drops or rises occurred, in the same way as a plant connected to the grid would do. Hence, the ability to adapt to changes of available wind power makes the ED very interesting for wind-powered brackish water desalination. However, the main limitation of the ED process itself, i.e. higher energy consumption than RO besides very low water salinity, has aroused the scientific community's interest in wind-RO applications up to the present.

As for RO, sustainable ED units for rural areas are compared with conventional fuel-powered membrane technologies, since most of the rural areas rely on diesel generators for their power supply. Abraham et Luthra [126] present a detailed economic analysis and comparison between PV powered and diesel generator powered ED desalination. The main features of a diesel generator were illustrated in subsection 1.2.1.

Photovoltaic-driven ED (PV-ED)

ED uses DC electricity for the electrodes at the cell stack, and hence, it can use the energy supply from the PV system without major modifications by using an inverter. For water circulation, the ED system needs also a low-pressure pump, which could be a DC or AC pump. The main advantage of combining ED with PV, compared to PV-RO, is that the process can work without inverter and - even if it is used - it would process only small amount of energy, thus saving energy losses. Figure 2.27 shows a schematic diagram of a PV-ED system.

Several experiments on ED systems connected to PV cells by means of batteries have been carried out [126, 129, 130]. These desalination units use batteries for the storage of the PV electric energy that is on its turn transformed in AC electric energy for powering the pumping system and the rectifier for the electrodialyzer.

However, the PV solar energy can be directly supplied to the ED system, without using a battery system, producing desalinated water during the sunlight hours. In this way, environmental problems related to the disposal of batteries are avoided as well as the sustainability of the process is increased. Moreover, pumping system could be powered by PV energy, since commercial PV recirculation pumps are available in the market. On the other hand, a small rechargeable battery - of very low consumption - may be necessary in order to power the control and measurement devices. Obviously, the absence of batteries implies that

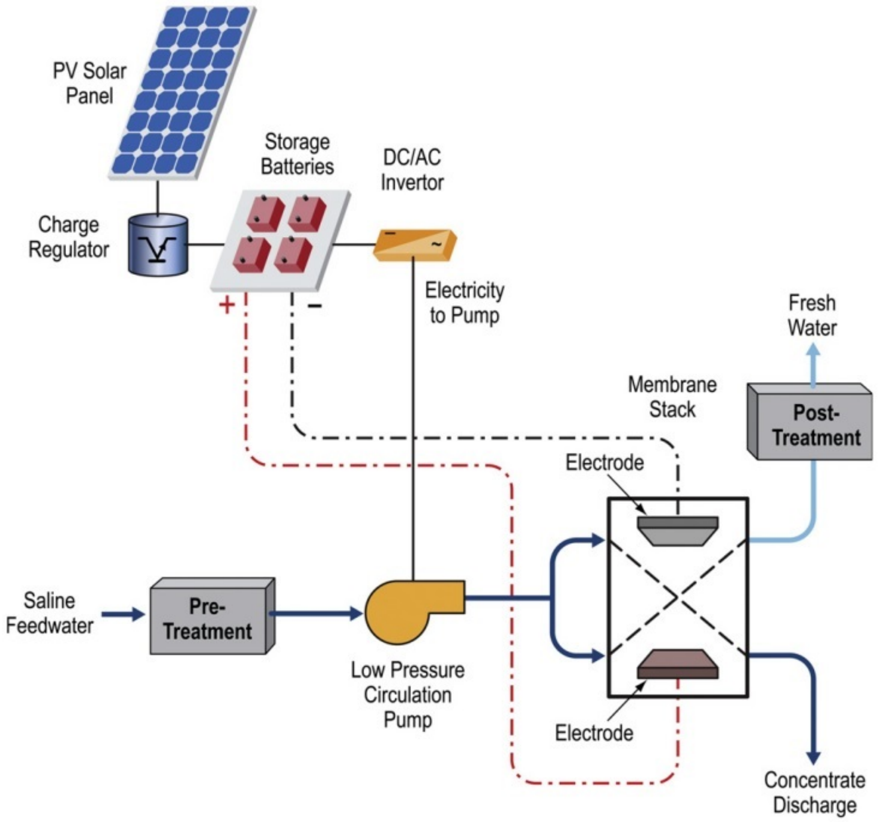

Figure 2.27: Schematic layout of a PV-ED unit with battery storage [44]

water production depends on and varies with the solar irradiation, which on its turn depends on meteorological conditions, geographical location, daily time, etc. Since desalinated water can be only produced during the sunlight hours, the ED system should have a higher capacity in order to meet the daily water demand, so the equipment and system maintenance costs will be incremented. In the last years, several studies test and analyze ED systems connected directly to PV cells [118, 120, 122, 131, 132].

2.3.2.5 Economics

Reviewing the available literature, a lack of experience on the economics of small-scale ED plants clearly emerges: an economic assessment of small-scale solar-powered ED units has been carried out only by few modeling and review studies so far and, furthermore, the retrievable information are often incomplete, contrasting and unwarranted [2, 39, 44, 52, 126]. Nevertheless, from these studies some useful information can be obtained:

		More economical than RO [ppm]	Suitability limit [ppm]
Sharon et Reddy [45]	2015	< 2,000	-
Abraham et Luthra [126]	2011	< 2,000	-
Al-Karaghouli et al [44]	2009	< 4,000-5,000	-
Kalogirou [47]	2005	-	6,000
Al-Karaghouli et Kazmerski [44]	2013	< 5,000	10,000
Hetal et al. [97]	2014	-	12,000
Ortiz et al. [122]	2008	< 10,000	36,000

Table 2.7: Review of assumptions on TDS and ED feasibility

- Even though quite wide, it is possible to set a range of WPC for PV-powered brackish water desalination from 3 to 16 $\$/m^3$, but more experience on on-field plants is required in order to demonstrate and to enhance the accuracy of the stated range.

- It is worthy to identify a range of total dissolved solids (TDS) contained in the feed water in which a renewable small-scale ED plant is usually cheaper than a RO one. Table 2.7 shows a comparison between the assumptions of different studies. The assumptions are quite contrasting; however, it can be affirmed that for TDS feed concentrations less than 5,000 ppm, ED tends to be more cost effective than RO, thus the implementation of a small-scale ED unit above a RO one must be considered.

- ED is widely considered to have demonstrate its economical feasibility only for brackish water applications. Hence, several studies recommend to consider the application of an ED plant only for TDS concentrations less than 10/12,000 ppm (see *suitability limit* in table 2.7). However, recently McGovern et al. [128] testing ED process for feed waters containing TDS of up to 192,000 ppm, concluded on the basis of energy and equipment costs, that ED processes are potentially feasible for the desalination of high salinity waters but they require further investigation under field conditions.

2.3.2.6 Comparison between PV-ED and RO applications

The desalination of brackish water using an PV-ED unit can have some important advantages compared to a PV-RO one, in particular if it does not use battery storage.

Concerning the desalination process, the main advantages are:

- Higher water recovery rates even for raw water with high sulphate content (85-94% recovery possible).

- Longer useful life of membranes due to higher chemical and mechanical stability (7-10 years).

- Less membrane fouling or scaling due to reversal process.
- Less raw water pretreatment.
- Easy start-up and shut-down of the process for intermittent operation.

From the point of view of using of PV solar panels as energy source, the advantages are:

- The ED reactor and the pumping system can be powered directly with DC current, and thus an inverter DC/AC is not necessary. This fact represents an energy saving because of the elimination of energetic losses in the transformation.
- In PV-RO - even in those that operate with DC pumps -, the solar panels converts the sunlight into electric energy, and after that, the electric energy is transformed into high-pressure mechanical energy. Hence, the process is composed by 3 steps with their respective energy losses. ED reactor is powered directly by the electric power from the solar panels instead, thus saving a step compared to the RO process, and then leading to an improvement of the efficiency of the process. On the other hand, there is a recirculation pumping system that must be also considered in the global consumption of the PV-ED system.

2.3.2.7 Final considerations

Due to the dependency of the energy consumption on the feed water salt concentration, the ED process is currently not economically attractive for desalinating seawater, whereas it tends to be the most competitive solution at low-concentration brackish water (less than 5,000 ppm) [44, 47, 52, 97, 101, 126].

In particular, as the process operates with DC power, PV panels can be conveniently used to directly produce the voltage difference required by ED process in areas with abundant solar resource. Moreover, in remote rural areas, the ED is most appropriate for brackish water desalination than RO because it is more robust than RO systems, its operation and maintenance are simpler and it is able to adapt to changes of available energy input [39, 47, 122, 126, 131].

Today pilot plants of small-scale ED systems connected to PV cells have been implemented [40], but mostly for R&D purposes and further studies and implementations are needed in order to assess properly both the technical and economical feasibility and appropriate applicability. The main barriers for this system are the high cost of PV cells, the limited availability of small-sized commercial EDR units and the suitability only for brackish water desalination [39, 40].

2.4 Brine treatment

All the desalination technologies reviewed in the current chapter are not able to cleanse the 100% of the feed water, hence a fraction of the feed flow has to be discharged after the process. This water outflow – called brine - has a very high concentration of salt, due to the partially conversion of the feed flow into fresh water. As for the seawater desalination, commonly the brine is discharged into the sea. On the other hand, brine disposal from inland brackish desalination is more difficult to be managed; the most commonly used solutions are: deep well injection, evaporation ponds, discharge into surface water bodies, disposal to municipal sewers and irrigation of crops tolerant to high salinity water [133].

The brine produced by desalination plants have a strong potential to spoil both physico-chemical and ecological attributes of receiving environments. Due to the great increasing of the world's desalination plants installed capacity, there is a growing concern about the environmental implication of discharging huge amount of brine into the environment. Therefore, new approaches that consider the sustainability of the whole desalination process, from the water intake to the brine disposal, are required.

According to José Morillo et al. [134], the following strategies for brine disposal have been developed:

- Technologies for reducing and eliminating brine disposal.
- Technologies for commercial salt recovery.
- Brine adaptation for industrial use.
- Metal recovery from brine.

The choice of the appropriate strategy and technology is influenced mainly by the volume and the quality of concentrate, the physical and geographical location of the discharge point and the capital and operational costs. Among all the currently available technologies addressing brine disposal, two are especially appropriate for the rural context: solar evaporation and phytodesalination.

2.4.1 Solar evaporation

Solar evaporation strategy consists in leaving the brine in shallow evaporation ponds, where water evaporates naturally thanks to the solar radiation. The salt left in the evaporation ponds is taken out for disposal. Evaporation ponds are relatively easy to construct and they require low maintenance. In addition, no mechanical equipment is required, except for the pump that conveys the wastewater to the pond, hence the operating costs are extremely low.

Evaporation ponds for disposal of brine from desalination plants need to be properly designed, maintained and operated in order to not create any negative effect on the environment, especially with regard to groundwater pollution.

The main drawback of the system is the large amount of area required. Moreover, this system is only appropriate for dry areas, where the natural evaporation rate is strong enough. Finally, this solution is appropriate only for small-scale systems.

2.4.2 Phytodesalination

Phytodesalination technology consists in employing the discharged brine for the crops field irrigation. The application of brine for crop production is limited due to low salt tolerance of most plants. However, approximately 1% of angiosperm species has evolved high salt tolerance, so that some of them are capable of growth and reproduction with a concentration of salinity exceeding the seawater one. These plants, usually called halophytes, allow crops production, according with the brine salt concentration: hence, a careful analysis of the quality of the discharged brine has to be carried out in order to employ phytodesalination. Potential products that may be derived from these halophytes include oilseeds, forages and biofuels. Nevertheless, when soils are irrigated with brine, excessive sodium can limit water infiltration, drainage and evaporation, making more difficult for plants to absorb soil moisture. Although phytodesalination is an attractive solution, it is still at an experimental stage of development.

Literature does not report specific solution for the brine disposal in rural areas. The analyzed studies on desalination technologies previously presented do not also mention the problem of the brine disposal. Hence, the brine management is not currently a main concern of the studies focused on small-scale, off-grid desalination system. However, the problem of the brine treatment cannot be underestimated, also in rural areas. Further research is needed, in order to develop appropriate solutions for this specific context.

2.5 Critical comparative review

In the previous paragraphs, a review of the various renewable energy desalination systems appropriate for off-grid rural areas applications was presented. It clearly emerges that the utilization of renewable energy for freshwater production can address three main problems: freshwater scarcity, environmental degradation and fossil energy depletion.

The selection of the appropriate desalination technology for rural areas depends on a number of factors, including: plant size, feed water salinity, remoteness, technical infrastructure and the type and potential of the local renewable energy resource on one hand, and availability of manpower, social fabric and people's willingness to pay on the other [47, 100]. Among the several possible combinations of desalination and renewable energy technologies, some seem to be more promising in terms of technological and economic feasibility than others. However, their applicability strongly depends on local circumstances and on the economics, environmental and social impacts of their application.

The review clearly points out that the difference in technological maturity compared to conventional desalination is reflected by the cost of the produced water (WPC), that is both quite undefined and higher than in conventional applications. De facto, several different figures are given in the scientific literature for the cost of each technological combination. These figures are calculated from pilot or demonstration systems as well as from design and modeling studies. However, the costs of these installations are greatly affected by the size and the local conditions. Moreover, the methodologies used to calculate these costs and the assumptions made vary considerably. Therefore, it is often quite difficult to directly compare these figures and to define accurate and reliable ranges of WPC for the analyzed technologies.

The present section introduces a comparative review of the described desalination technologies, through a critical analysis of the scientific literature.

The comparison is based on the widely-used parameters and indicators already introduced during the analysis of the technologies. In particular, it was decided to take advantage of a set of parameters of performance such as energy requirements, freshwater quality and water production cost; a set of technical parameters such as unit size, lifetime and required replacements and other important parameters such as the technical development stage, that are essential in order to evaluate the proper applicability of a technology.

2.5.1 Comparative review

Two synthetic tables are reported in order to support the comparative review of the analyzed desalination technologies. Table 2.8 reports the distinct features of the technologies in terms of advantages and disadvantages. A comprehensive performance and technical analysis of the desalination systems is then illustrated in Table 2.9.

The reported figures and statements refer to the literature already presented and quoted in the previous sections.

	Solar still	**HDH**	**MD**
PROS	Well-proven technology Simplest desalination technology: no technical maintenance It can be constructed using local manpower and materials Suitable for home-based production High water quality, no pretreatment is required Operation at atm. pressures	Higher specific yield than solar stills Simple and easy to maintain More flexible than solar still High water quality, no pretreatment is required Operation at atm. pressures	Promising technology. A remarkable number of studies are focused on MD Low operating temperatures High water quality, no pretreatment is required Simpler and cheaper membranes than RO Operation at atm. pressures
CONS	Very low specific yield: large area required Very low thermal efficiency	Electrical energy in addition to the thermal one is required Not fully commercially developed	Expensive technology Large membranes surface area Further research is required

	RO	**ED**
PROS	Low energy consumption Flexibility in capacity expansion (modular design) Operation at ambient temperature Ease of operation and fast start-up Highly suitable for coupling with different renewables	High water recovery (85 – 94 %) Membranes have longer life because of better stability (7 – 10 y.) Reduced membrane fouling or scaling Easy start up and shut down of the plant Less raw water pretreatment is required than RO Can be operated with DC: high suitable for PV coupling and no inverter is needed (reduced losses) Operation at low pressures
CONS	Membranes usually have short life (5 – 7 y.) Pretreatment of feed water is required Biological fouling of membrane is possible Energy consumption and WPC increases with salinity: not suitable for feed water with more than 60k ppm High capital costs if coupled with renewables	Micro-organisms remain in the product water Energy consumption and WPC highly increase with salinity: only suitable for feed water up to 10/12k ppm Reversal of polarity is needed every 20 min to prevent salt deposition on the membranes High capital costs if coupled with PV

Table 2.8: Distinct features of desalination technologies for rural areas

	Solar Still	**HDH**	**MD**	**Res-RO**	**PV-ED**
Unit size [m^3/d]	< 0.1	1 - 100	0.15 – 10	0.1 – 100	0.1 - 100
Lifetime unit [y]	5 – 10	20	20	20	20
Required replacement [y]	-	-	Membr: 3 - 7	Membr: 5 – 7 Batteries: 5 Chemicals	Membr: 7 – 9 Batteries: 5 Chemicals
Operating temperature [°C]	20 – 90	100	50 – 90	20 - 40	20 - 40
Heat consumpt. [kWh/m^3]	650	100	150 - 200	-	-
Electric consumpt. [kWh/m^3]	-	1.5	Negligible	BW: 1 – 3 (2) SW: 3 – 10 (5)	BW (< 3000 ppm): 0.7 – 2.5 (1.5)
Primary En. consumption [kWh/m^3] *	650	104	150 – 200	BW: 6 SW: 15	BW (< 3000 ppm): 4.5
Pretreatment	No	No	No	High	High
TDS freshwater quality [ppm]	< 10	< 10	< 10	SW: < 500 BW: < 200	140 - 500
Tech. development stage	Commercial	Pre-commercial	Advanced R&D	Commercial	Advanced R&D / pre-commercial
WPC [$/$m^3$]	2 – 15	2 – 13	10.5 – 19.5	PV-BWRO: 2 - 7 PV-SWRO: 4 - 11 Hybrid-RO: 2 - 5	BW: 3 - 16

* Assumed conversion efficiency of electricity generation of 33%

Table 2.9: Performance and technical comparison of desalination technologies for rural areas

Energy requirement Different factors have influence on energy consumption, including: plant capacity, unit design, materials used, power system, environmental conditions and the seawater feed stream quality.

Comparing the technologies, it can be noticed that the distillation processes require higher energy than membrane ones of one or two orders of magnitude. This is due to two main reasons: the high amount of energy needed for water vaporization and the continuous improvement in the technology of the RO process membrane and of the recovery system, which resulted in lower power consumption. In particular, the energy consumption of solar still is found to be the largest due to loss of latent heat of condensation dissipated to the ambient, whereas HDH and MD require small amount of electricity to drive the circulation pumps, in addition to their significant thermal requirement.

It should be noted that the energy consumption in distillation processes is not influenced by the salt concentration of the feed water, whereas it is highly influenced by the salt concentration in the membrane processes.

It should be noted that, thanks to the distillation by means of evaporation, thermal desalination plants are not affected by the feed water quality: they can treat brackish water as well as seawater, with great results in terms of TDS (< 10 ppm) and with no effects on the energy requirements. Due to the increasing of the energy demand with the salinity of the feed water, it is generally stated that ED and RO processes are not appropriate for producing adequate fresh water for TDS feed concentrations more than 12,000 and 60,000 ppm respectively.

Lifetime and replacements A conventional solar still has a very short lifetime comparing with the other desalination systems; hence, during a supposed 20-years project, it's necessary to replace the device three or four times. On the other hand, ED, RO and MD have to replace periodically the membranes. Moreover, RO and ED units employing battery storage and chemicals for pretreatment and post-treatment have to take into account also their replacement.

The lifetime of the solar collectors employed by MD and HDH, which is usually 20 years, might decrease due to the environmental conditions of the rural areas.

Maintenance Solar still is the simplest desalination technology. It requires routine maintenance to prevent scale formation but the maintenance implies only very elementary cleaning operations, practicable by non-technical manpower. PV-powered membrane processes are also characterized by ease of operations but they require more maintenance than solar still anyway: PV panels have to be frequently cleaned but qualified manpower is not needed, whereas occasional necessary operations and maintenance on chemicals and membranes make appropriately trained and qualified technicians recommended. Rechargeable batteries eventually used also require periodic maintenance. In particular, an ED unit is more robust and its operation and maintenance are simpler than RO systems.

Solar collectors employed by HDH and MD need of a non-qualified regular maintenance. The circulating pumps used by HDH and MD are characterized by ease of operations; however, a proper maintenance has to be carried out.

Pretreatment and post-treatment Membrane processes need significant pretreatment and post-treatment in order to protect the membranes and to ensure freshwater quality. The distillation allows the thermal processes to operate without any water treatment system: water evaporation ensures that the distilled water does not contain any micro-organisms, heavy metals, etc. Hence, in high polluted areas, thermal processes are preferred to the membrane ones. Even a basic solar still can provide removal efficiencies in the order of 99%. A simple pre-filtration system might be used in HDH and MD to protect the feed pump from solid materials. A re-mineralization might be employed in thermal processes to improve the taste of the freshwater produced.

On the membrane processes side, improvements in pretreatment processes (including nano-, ultra- and micro-filtration membranes) are recently being implemented and most of the new medium-scale RO plants are using lesser amounts of chemicals, thus experiencing a great reduction in operating costs.

Storage The three thermal desalination processes do not require continuous operation, they can work with intermittent energy supply without additional modifications and energy storage, which makes them suitable for a intermittent energy sources such as solar. A thermal storage is seldom used to increase the exploitation of the solar resource, but it is not necessary. An array of batteries is often used as backup system in the membrane processes, especially with RO, in order to power the desalination unit by night and to achieve a stable operation, thus preserving the life of the membranes. A diesel generator can represent a good alternative to a costly, inefficient and short-living battery storage as a back-up system.

In order to provide fresh water when the power supply drops, a communal solution is to integrate into the system a water tank, since water is an excellent storage medium and can be stored in vast quantities for extended periods of time.

Technical development stage Solar still and small-scale RO units are fully commercially available technologies: they have both already been tested extensively and the WPC are estimated based on operational experiences. Solar stills have undergone many modifications and improvements, but they are not currently experiencing notable enhancements of performance, whereas RO systems are facing continuous improvements both in the performance of RO process (namely in membranes, pretreatment processes and energy recovery systems) and in performance of the renewable system powering the process (in particular in decreasing PV modules and wind generators costs). HDH and PV-ED are currently opening up to the small-scale off-grid areas market but they have limited practical experience yet. Nowadays, MD employed for desalination is attracting more attention but further research is needed to reach the commercial stage.

Water production cost The WPC of desalination units is affected by the analyzed factors. In particular, the difference in technological maturity together with the strong dependence between technologies performance and local context is reflected by the definable cost of the produced water: it is often quite difficult to define accurate and universal ranges of the WPC of the analyzed technologies and to directly compare these figures. The economic analysis carried out so far have not been able to provide a strong basis for comparing economic viability of each desalination technology. The economic performances expressed in terms of cost of water production have been based on different system capacity, system energy source, system component, water source and environmental conditions. These differences make difficult, if not impossible, to assess the economic performance of a particular technology and compare it with others.

2.5.2 Final remarks

There is no *best* method of desalination. The selection of a process should depend on a careful study of site conditions and the application at hand. Local circumstances may play a significant role in determining the most appropriate process for a rural area. However, some final remarks on the suitability and proper applicability for rural areas of the studied desalination technologies can be stated.

Membrane technologies such as RO and ED seem to be currently the most cost-competitive solar desalination technologies for small/medium-scale applications in several rural areas. In particular, thanks to the continuous fall of the production costs for PV cell industry, PV-RO[7] is a potential solution. As a matter of fact, PV-RO has minimal environmental impact, can be easily designed and assembled for different demand profiles using modular components and it can be easily maintained and repaired, thus being a promising sustainable solution not only economically but also environmentally and socially. For low salinity brackish water desalination, ED is most appropriate since it is more robust and its operation and maintenance are simpler than RO systems. In addition, ED process is able to adapt to changes of available energy input and, operating with DC current, it is high appropriate for PV coupling.

In some specific circumstances, i.e. high polluted or high feed water concentration areas, the economics and the sustainability can shift in favor of the distillation process.

Solar still requires a large area for solar collection so it is only viable for very small-scale production ($< 0.1\ m^3/day$). In particular, it can be the cheapest desalination solution in rural areas where solar energy, proper materials and manpower are abundant. Moreover, its easier construction using local available materials and manpower, its minimum operation and maintenance requirements and friendliness to the environment make the solar still a promising sustainable solution for very small freshwater requirement also from a social end environmental point of view. HDH is a natural development of the solar still, since it is more efficient; however, it does not have the same characteristic of simplicity and ease of construction.

Recent developments in indirect solar desalination focuse on MD as it combines the advantages of both membrane and thermal desalination technologies such as operation on thermal energy, ability to desalinate high salinity water, minimal pretreatment and fouling resistant. Although currently its energy requirements are still high with low recovery ratio, the distillate output from MD is estimated to be 4.5 times the output from a solar still.

As a matter of fact, there is a growing need for on-going research and demonstration projects to gain experience, knowledge and trust in these new small-scale off-grid sustainable desalination technologies. These measures would most likely result in a better understanding

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[7] with or without diesel generator as backup system in place of battery storage

of the economics, environmental and social peculiarities of a desalination project and in lower energy consumption and production cost of desalinated water, thus enhancing the sustainability of the desalination project itself.

Hence, collective and comprehensive research and development programs involving all the actors involved in a rural area desalination project - consumers, NGOs, local communities, governments, industries, universities and research institution - are required to develop simple, low maintenance, sustainable renewable energy systems that can supplement power supply for small desalination facilities in order to tackle in a sustainable way the water scarcity in rural areas of developing countries.

Chapter 3

A multi-criteria approach to rural desalination

In the previous chapter, several desalination technologies were analyzed, thus enlightening weaknesses and strengths of each technology. The identification of the technology that best suits a specific local context must be handled.

Because of the advantages and disadvantages of each desalination technology and due to the diversity of objectives and constraints that should be considered and satisfied simultaneously, the selection of the optimum technology for a specific area is a complicated task. Moreover, especially in rural areas, there always exists a lack of sufficient data, which adds an extra dimension of complexity. In such situations where the decision-maker (or the decision-makers) has to deal with many criteria and constraints, it is a good solution to use a decision method, i.e. a procedure that allows a decision-maker to analyze a situation setting a series of rules in order to evaluate the alternatives and to choose the best one in accordance with the rules set before [135, 136].

3.1 State of the art of multi-criteria approaches

3.1.1 A glance over multi-criteria decision methods

Multi-criteria decision analysis (MCDA) methods have become increasingly popular in decision-making for sustainability because of the multi-dimensionality of its goal and the complexity of the economic-social-environmental systems [137].

Multi-criteria methods include two big families of methods: multi-objective and multi-attribute. Multi-objective methods search the optimal solution of the problem optimizing a mathematical function among infinite possible solutions. Therefore, they are not appropriate for a rural desalination problem, since the appropriate technologies are a limited number. The necessity to choose among a finite number of alternatives leads to select a multi-attribute method, that determines a rank among n given alternatives and makes the decision-makers able to choose the best one.

Multi-attribute decision methods require that the decision-makers determine some fundamental elements that characterize the model [135]:

- the goal, i.e. the final and general objective to which the decision-makers strive for;
- the criteria used by the decision-makers to evaluate and compare the alternatives (possibly break down in sub-criteria);
- the alternatives themselves.

After the definition of the structure of the model, four main stages are generally included in the method: alternatives formulation and criteria selection, criteria weighting, evaluation and final treatment and aggregation. The preliminary step in MCDA is to formulate the alternatives for the problem from a set of selected criteria and to normalize the original data of criteria. Secondly, criteria weights are determined to show the relative importance of criteria in MCDA. Then, the acceptable alternatives are ranked by MCDA methods with criteria weights. Finally, the alternatives' ranking is ordered [138].

Commonly used MCDA methods include the Analytical Hierarchy Process (AHP), Goal Programming, Multi-Attribute Global Inference of Quality (MAGIQ), Simple Multi-Attribute Rating Technique (SMART), SIMOS, etc [139]. Therefore, in order to choose the most appropriate method to be applied in a rural desalination project, the main characteristics of the problem must be evaluated:

- a rural desalination project involves different stakeholders, each of which can have different objectives, criteria and even influence towards the project itself;
- several indicators of the chosen criteria must be evaluated qualitatively, since it is really difficult to obtain reliable quantitative data in rural contexts.

3.1.2 The Analytic Hierarchy Process

Taking into account the type of the considered problem (rural desalination) and the indicators used to assess it (qualitative and quantitative ones, see section 3.2), the method that seems to have the most appropriate characteristics to make a comparison among alternatives is the Analytic Hierarchy Process (AHP), proposed by Tomas L. Saaty.

The AHP provides a comprehensive framework by considering quantitative and qualitative factors based on the intuitive and rational/irrational judgments of the respondents. The method requires the breaking down of the problem in smaller and simpler elements (hence *analytic*) in different levels of *hierarchy* and then it calculates the weight of the factors with a pairwise comparison at all the hierarchic levels of the problem [140].

Other researchers have utilized AHP for research examining subjects such as multi-criteria decision-making in energy planning [141, 142, 143], making sustainable energy development strategies [139, 140] and selection of desalination plants [136, 144, 145].

Each step of the model is now described.

3.1.2.1 Hierarchical breaking down of the problem

The first step of an AHP analysis is to build a decision hierarchy by means of breaking down the decision problem into a hierarchy of its elements (see figure 3.1).

The goal, i.e the objective of the decision-makers, lies at the top of the hierarchy.

The criteria levels are located below the goal. A criterion is a measurable aspect of a judgment, which makes possible to characterize and quantify alternatives in a decision-making process. There might be several criteria levels since each criterion can be broken in sub-criteria. A deeper breakdown of the problem leads to an higher precision in the resulting decision.

The alternatives, which have to be evaluated with respect to each criterion by means of a set of indicators, lie at the bottom level. Each criterion could need one or more indicators, that must be carefully defined before going on with the decision process. The indicators can be qualitative or quantitative.

Moreover, it is possible to assign for each stakeholder different weights, thus considering the relevance and competence of each decision-maker with respect to each criterion.

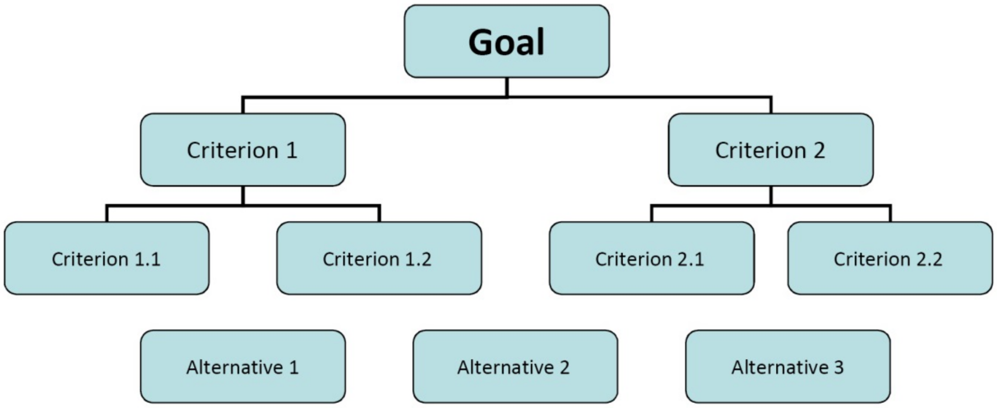
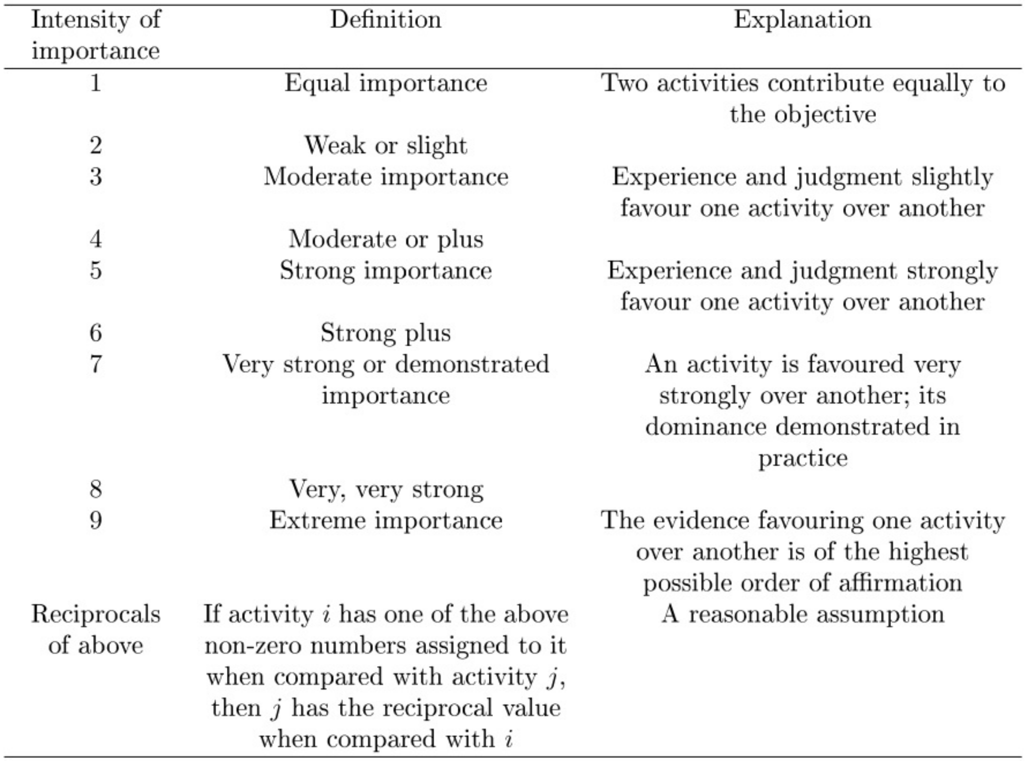


Figure 3.1: Example of AHP hierarchy breakdown [135]

3.1.2.2 Ratings based on pairwise comparisons

The second step of the analysis is to compare each element of a hierarchy level to the others of the same level, i.e finding the weight of the element respect to the others. Considering a three-level hierarchy as shown in figure 3.1, the alternatives must be rated in respect to the criteria *1.1*, *1.2*, *2.1* and *2.2*. Hence, criterion *1.1* and *1.2* must be judged within criterion *1*. In the same way, the right side of the hierarchy (criteria *2.1*, *2.2*, *2*) must be evaluated. Finally, criteria *1* and *2* are evaluated in respect to the goal.

In the AHP model, the described comparison of the different alternatives and criteria is based on pairwise comparisons, thus evaluating the relative performance of the alternatives without considering the absolute one (sometimes absolute performances are difficult to be estimated). To make each pairwise comparison, the fundamental scale of Saaty is used [146]. The scale is based on numbers from 1 to 9, where 1 indicates that the two compared elements have the same importance within the considered criterion and 9 indicates that the first element have extremely better performance than the second one, as shown in figure 3.2. If the first element is less important than the second one, a number between 1/9 and 1 is used.



Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favour one activity over another
4	Moderate or plus	
5	Strong importance	Experience and judgment strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption

Figure 3.2: The fundamental Saaty's scale of absolute numbers [135]

Qualitative indicators can be evaluated directly through Saaty's scale, whereas the quantitative ones must be normalized and then converted to the same scale (for further details see [135]).

The pairwise comparison matrix about a generic criterion A is:

$$[A] = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{21} & \cdots & a_{2n} \\ \vdots & \vdots_{32} & a_{ij} & \vdots_{3n} \\ a_{n1} & a_{n2} & \cdots & a_{4n} \end{bmatrix}$$

Where:

- a_{ij} represents the comparison between element i and element j
- $a_{i=j} = 1$
- $a_{ij} = \frac{1}{a_{ji}}$

3.1.2.3 Synthesis of the priorities and hierarchy building

Once the pairwise comparisons have been settled, it is necessary to aggregate the data, in order to establish a hierarchy between the alternatives towards the goal. From each comparison matrix a priority vector can be calculated, i.e a vector whose elements correspond to the importance of each alternative within the considered criterion. The elements of this vector are numbers ranging from 0 to 1; the higher the number is, the more the alternative is relevant with regard to the criterion. The same procedure has to be applied to the comparison matrices of the upper levels, up to the goal.

AHP uses a principle of hierarchic composition: the priorities of each alternative within multiple criteria are obtained multiplying each priority of an alternative by the priority of its corresponding criterion and adding over all the criteria to obtain the overall priority of that alternative. The final result of this process is the global priority vector, i.e a vector whose elements correspond to the importance of each alternative within the goal. The alternative with the highest priority is the one that best fits the criteria defined by the decision-makers.

It's beyond the scope of the current research to explain in detail how the priority vectors are calculated; for further information see [135, 146, 147].

3.1.2.4 Analysis of the results

Once the priority vectors have been identified, it is important to verify if all the judgments made in the pairwise comparisons matrices are coherent, before the decision has been taken. As a matter of facts, the decision-makers cannot easily fill in the matrices in a reliable way; hence, it is important to have a tool that helps to verify the pertinence of the comparisons. This tool is the consistency test, which checks if the comparisons respect some logical rules as the principles of transitivity and reciprocity. The test verifies if the value of the consistency ratio (CR), i.e. a number extracted from the pairwise comparison matrix, is lesser than a fixed value, usually set equal to 0.10 [147].

However, the coherence of the comparison matrices is necessary, but not sufficient to achieve a reliable decision. AHP is affected by the subjectivity of the decision-makers; thus, it is important to verify that small changes in the decision-makers opinion do not lead to a different hierarchy of the alternatives. In order to find out the range where the solution is stable, a sensitivity analysis on the criteria weights is usually performed. Many other types of sensitivity analysis are proposed in the literature [148, 149].

3.1.2.5 Limits and strengths of the model

As it was already stated, the AHP model can be employed to help decision-makers involved in rural desalination project. However, it is important to remark some limits of the model:

- The computational procedure is very long, especially when a great number of alternatives or criteria are possible.
- The normalization of the quantitative indicator might lead to wrong solutions. As a matter of facts, the conversion of the quantitative indicators to the Saaty's scale does not take into account the real distances between the alternatives [135].
- The most important weakness of the AHP model is the so-called rank reversal [147]: in certain condition (especially as the number alternatives increases) the addition or the removal of an alternative could bring to a rank reversal among two or more other alternatives. This phenomenon can appear also when the added (or removed) solution should not influence the rank of the other ones, for example because it is the worst alternative or it is similar or equal to another one.

In spite of these drawbacks, the AHP is chosen for the following strengths:

- The AHP is able to employ both quantitative and qualitative criteria. Therefore, it is not necessary to know the exact values of the indicators but only to estimate them, even qualitatively.
- The construction of a hierarchy makes possible to break down any kind of problem, even a very complex one, in simpler elements, thus making the definition of the set of indicators easier.
- The pairwise comparisons employed in the method are user-friendly.

3.2 Rural desalination: an AHP application

As it was stated in the previous section, among the others, AHP is selected as the most appropriate multi-criteria method for off-grid rural desalination applications. Hence, in the current section, the application of the AHP method to the choice of the best desalination alternative for a specific rural context is illustrated. The purpose is to give a tool to non-technical decision-makers - who have already decided to face the water scarcity of a rural area through a water treatment process - that might help them to evaluate the acceptable alternatives in order to choose the most appropriate one in accordance with their priorities. Usually, the involved decision-makers are part of NGOs, international organizations, regional or central governments.

De facto, the critical review carried out in chapter 2 leads to a deeper understanding of the parameters that characterize each alternative. Moreover, the knowledge of the behavior of the rural context in developing countries points out the relevance of some of the alternative's features towards this peculiar context. Therefore, as an output of the critical review of the state of the art of off-grid rural desalination, it is possible to build an appropriate decision hierarchy of the problem and to define a proper set of indicators that allow to evaluate and to compare different acceptable alternatives.

The water scarcity issue in rural areas involves many different stakeholders, which might have different objectives and different competences: a project aiming to answer that issue has to take into account each stakeholder opinion. Among these stakeholders, it is important to recall the presence of the local institution, the local community and the households. The decision-makers, thanks to a deep knowledge of the local context and of the hierarchy criteria, have then to give a proper weight to each stakeholder's judgment, in accordance with their competence and relevance.

Although the logic framework of the model, the criteria and the indicators should remain the same, the judgment data collection should be shaped according to the competence, culture and relevance of each stakeholder. For instance, an AHP comparison matrix can be filled in directly by a local government, whereas a simpler questionnaire might be more appropriate for gathering the opinion of a local community.

The employment of the present method will enhance the project's ownership of the stakeholders since the AHP method follows a bottom-up process: the best solution is achieved by consulting each stakeholder and by weighting his judgments. Therefore, the most appropriate desalination solution comes out from the interaction between the local needs and resources, and the competences and objectives of the decision-makers.

3.2.1 Hierarchy

Once decided to use the Analytical Hierarchy Process method, it is necessary to precisely define the hierarchy of the problem that must be solved, as explained in subsection 3.1.2.

The problem is to choose between various alternatives in order to identify the most appropriate solution able to provide freshwater in rural areas in a sustainable way according to the local context. The goal (i.e. the top level of the hierarchy) has to be defined consequently as '*freshwater provided*'.

As a logical consequence of the concepts explained in subsection 1.1.4, in order to be sure to evaluate all the aspects of sustainability, the three dimensions of sustainability (*Economic*, *Environmental*, *Social*) coincide with three fundamental criteria (*Economic criterion*, *Environmental criterion*, *Social criterion*), which represent the second level of the hierarchy.

Each of these fundamental criteria is then evaluated based on several specific sub-criteria, which together constitute a third level of the hierarchy.

The choice of the sub-criteria - as well as of the respective indicators described in the following paragraph (both illustrated in table 3.1) - is based on guidance provided by IAEA and United Nations regarding the themes that make up the three dimensions of sustainability [20, 21]. In order to take into account the specific issues of the analyzed problem, researches on the application of AHP and multi-criteria methods in sustainable development projects in the South African context [150], in the selection of desalination plants [136] and in sustainable energy decision-making [139] were also analyzed.

Moreover, from the critical review illustrated in chapter 2 some useful guidelines on the definition of proper indicators emerge:

- The water production cost stands out as the key parameter for evaluating the economic performance and sustainability of a desalination technology. At the same time, the high capital cost of the employed energy system can be a heavy drawback of some membrane solutions.
- The soil consumption emerges as a serious environmental issue for renewable-powered desalination, in particular for solar thermal processes. An appropriate brine disposal is mandatory for each solution. Diesel generators conveniently used as backup systems in hybrid-RO configurations might have a non-negligible impact on the local atmosphere.
- Technological peculiarities as modularity, type of energy requirement and easy of construction and maintenance can lead different desalination solutions to have different impacts on social benefits and local employment.

It is important to underline that it is assumed that eligible alternatives have already been selected by the decision-maker (o decision-makers) on the basis of a criterion of technical feasibility. For example, some alternatives employ renewable energy systems that might be not conveniently implemented in some areas due to the lack of the exploited renewable resource. It can be also possible that some technologies do not experience an adequate technological development stage to be actually available in the market. Therefore, the goal is to select the alternative that gives the best compromise between the three dimensions that make up sustainability, assuming that the alternatives that are not feasible from a technical point of view have already been rejected.

3.2.2 Indicators

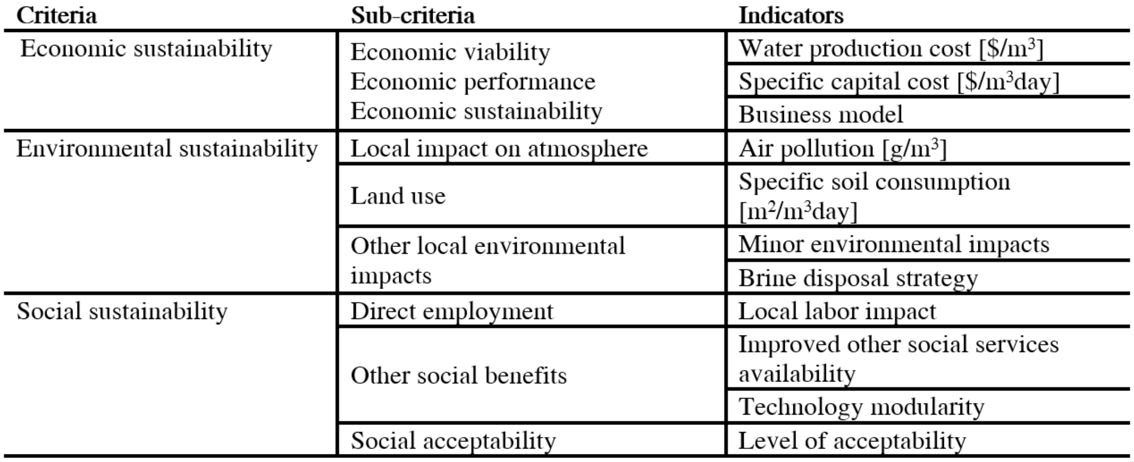
It is necessary to identify a set of indicators in order to give an estimation of the performance of each alternative with respect to each criterion and sub-criterion in the form of quantitative data or, when it is not possible, in the form of qualitative judgments, as seen in subsection 3.1.2.

Hence, the selection of indicators is based on three main criteria, as suggested by the Commission on Sustainable Development of the United Nations [20]:

> "Core indicators fulfill three criteria. First, they cover issues that are relevant for sustainable development in most countries. Second, they provide critical information not available from other indicators. Third, they can be calculated by most countries with data that is either readily available or could be made available within reasonable time and costs"

As a matter of facts, typically the choice among the possible alternatives takes place during the early stages of the project. For this reason, indicators that require very specific and detailed information are not realistically eligible. In any case, not to exclude aspects that are difficult to evaluate from a numerical point of view, alongside quantitative indicators qualitative indicators are proposed, too. Quantitative indicators assume values that are directly collected from a pre-feasibility study or are calculated on the basis of other available data. Qualitative indicators, at the contrary, are based on a reasoned evaluations performed by the decision-makers.

A scheme of the defined hierarchy is shown in figure 3.3. Selected indicators for each sub-criteria are listed in table 3.1.



Criteria	**Sub-criteria**	**Indicators**
Economic sustainability	Economic viability Economic performance Economic sustainability	Water production cost [$\$/\mathrm{m}^3$]
		Specific capital cost [$\$/\mathrm{m}^3\mathrm{day}$]
		Business model
Environmental sustainability	Local impact on atmosphere	Air pollution [g/m^3]
	Land use	Specific soil consumption [$\mathrm{m}^2/\mathrm{m}^3\mathrm{day}$]
	Other local environmental impacts	Minor environmental impacts
		Brine disposal strategy
Social sustainability	Direct employment	Local labor impact
	Other social benefits	Improved other social services availability
		Technology modularity
	Social acceptability	Level of acceptability

Table 3.1: Selected indicators and sub-criteria for for rural desalination problems

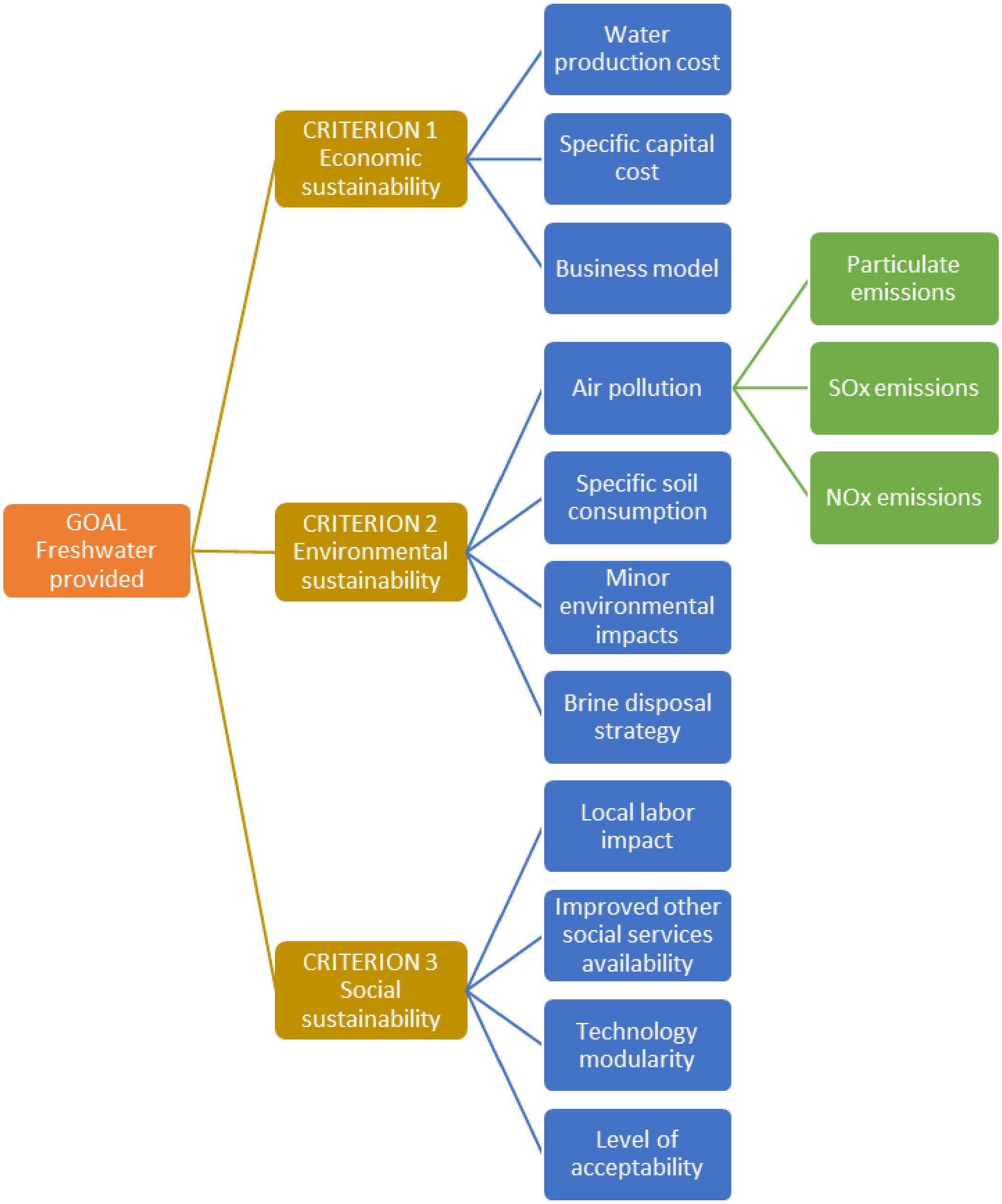


Figure 3.3: Scheme of the hierarchy for rural desalination problems

3.2.2.1 Economic dimension indicators

The selected economic indicators are three: *water production cost*, *specific capital cost* and *business model indicator*. Clearly, they provide an indication in accordance with the sub-criterion of the economic dimension: economic viability, sustainability and performance. In particular, as explained in the following paragraph, the *business model indicator* does not describe the economic performance itself but it is crucial in order to assess the economic sustainability of an alternative.

Water production cost (WPC) [$\$/m^3$]

Sub-Criteria: Economic viability, sustainability and performance

Type: Quantitative

Description: *Water production cost* indicator represents the cost of the water produced over the lifetime of a desalination plant, expressed per unit of water. It is calculated as:

$$WCP = Total\, annualized\, cost/Total\, water\, production$$

Where:

Total annualized cost is the sum of each annualized cost related to the system. Therefore, it includes capital costs, operation and maintenance costs and replacement costs.

Total water production is the amount of water produced during the project lifetime.

The indicator is very useful to understand which the cheapest solution is, since it takes into account all the incurred expenditures.

The alternative that can generate freshwater at a lower cost is considered better.

Specific capital cost [$\$/m^3 day$]

Sub-Criteria: Economic viability, sustainability and performance

Type: Quantitative

Description: The specific capital cost consists of total expenditure incurred in establishing a desalination system - including the equipment, labor, installation, infrastructure and commissioning cost - per 1 m^3/day of producing capacity. This parameter is less complete than the water production cost, since it does not take into account replacement, operation and maintenance costs. De facto, the capital cost is already considered within the water production cost. However, the capital cost grows in interest considering the rural context: as a matter of facts, rural areas do not have a strong credit system; thus, it might be very difficult to raise the money required by a capital-intensive system. Therefore, although having the same water production cost, a system requiring lower capital cost is more feasible and it enhances the sustainability of the project.

The alternative that has less capital cost is considered better.

Business model indicator

Sub-Criterion: Economic sustainability

Type: Qualitative

Description: A business model is the plan implemented by the decision-maker to generate revenues. De facto, it describes how an organization creates, delivers and captures value in economic, social and cultural contexts. Since a desalination project lasts for some decades, it is important to establish a business model able to guarantee the economic sustainability over the years. The most appropriate business model must be identified by the decision-maker depending on the peculiarities of the local context. Hence, the indicator does not evaluate the business model itself: the decision-maker has to assign a value to the indicator according to how much each alternative matches the selected appropriate model. For instance, if the decision-maker identifies a decentralized model where every household manages its own desalination device as the most appropriate for a certain context, a solar still is certainly a better alternative than a complex RO system.

3.2.2.2 Environmental dimension indicators

The environmental indicators are selected in order to describe the local environmental impact of a desalination plant. Since the method compares technologies appropriate for small-scale rural applications, global environmental impact indicators such as the life cycle assessment of the CO_2 production are not considered. De facto, small-scale technologies do not have a significant impact on the global context. It should be noted that this is a great difference with traditional large-scale desalination technologies, which have a great global environmental impact instead.

The other indicators consider the soil consumption, particularly crucial for thermal desalination technologies, and the brine disposal strategy.

Air pollution [g/m^3]

Sub-Criterion: Local impact on atmosphere

Type: Quantitative

Description: Desalination systems powered by fossil fuels might pollute the local environment due to particulate, SOx and NOx. These pollutants have serious human health impacts and ecosystem impacts: they usually lead to respiratory problems and cancer and they can be lethal to aquatic and terrestrial plants and animals. Hence, improving air quality is a significant aspect of promoting sustainable settlements.

'Air pollution' indicator reports the quantity of emitted pollutant per cubic meter of freshwater produced and it is obtained from the aggregation of three sub-indicators: particulate, SOx and NOx.

Particulate. Emissions of particulate deriving from the process.
SOx. Emissions of SOx deriving from the process.
NOx. Emissions of NOx deriving from the process.

The alternative that emits less pollution is considered better.

Specific soil consumption [m^2/m^3day]

Sub-Criterion: Land use

Type: Quantitative

Description: The indicator refers to the amount of area required by the desalination system for 1 m^3/day of freshwater producing capacity. The calculated area must include the area occupied by the desalination unit, the energy system and the utilities (when required). For instance, several desalination systems employ solar thermal energy, thus implying a large area that has to be located near the village in order to guarantee a proper control. Therefore, an alternative might be in competition with other land usages. An assessment of the local land availability must be carried out, identifying the availability of each different category of land use (arable land, permanent cropland, forests, built-up areas, building areas, etc.), in order to understand the actual impact of the desalination system on the criterion 'Land use'.

The alternative that occupies less land is considered better.

Minor environmental impacts

Sub-Criterion: Other local environmental impacts

Type: Qualitative

Description: This indicator takes into account other minor impacts - such as noise, bad smells, etc. - that a desalination system might have on the local environment. Since it considers different types of phenomena, measured in different ways, the indicator has to be a qualitative one. Moreover, the weight of this indicator should be small, since usually the possible minor impacts are not of serious concern in water- and energy-scarce areas.

The alternative that has less minor environmental impacts is considered better.

Brine disposal strategy

Sub-Criterion: Other local environmental impacts

Type: Qualitative

Description: A desalination technology produces a brine outflow, which can be harmful for the environment if it is not properly treated. The selected alternative must comprehend a brine disposal strategy, in order to minimize its environmental impact. Therefore, the brine disposal strategy indicator evaluates the environmental effects of the brine produced and treated by the selected alternatives. A small weight should be assigned to this indicator if the identification of the brine disposal strategy is not influenced by the selected desalination technology.

The alternative that has minor environmental impact with brine disposal is considered better.

3.2.2.3 Social dimension indicators

This group of four indicators gives information about the impact of the considered alternatives on the local population in relation to the improvement of social benefits (mainly related to the water and the energy access conditions), the consequences on health and eventually the direct and indirect improvement of employment.

Local labor impact

Sub-Criterion: Direct employment

Type: Qualitative

Description: Desalination projects generate employment opportunities especially for the local communities. This indicator refers to the number of people recruited from the local community for the employment of an alternative. Additional local direct and indirect opportunities created or destroyed and the possible indirect creation of new professional figures are also assessed. Since a quantitative estimation of the number of people involved is very critical, the indicator is evaluated in a qualitative manner.

The alternative that creates more job opportunities is considered better.

Improved other social services availability

Sub-Criterion: Other social benefits

Type: Qualitative

Description: This indicator is used to value the ability of an alternative to provide other services than clean water supply to the local community. For example, membrane technologies as RO and ED can provide electrical connections and electricity backup service to the local community. Electrification of the local community is considered a very important social benefit for remote settlements and villages that experience water and energy scarcity.

Alternative with more improvement of availability of social services to the local community is considered better.

Technology modularity

Sub-Criterion: Other social benefits

Type: Qualitative

Description: This indicator estimates the modularity of the technologies employed in each alternative. When a product or process is "modularized", the elements of its design are split up and assigned to modules according to a formal architecture, thus allowing to accommodate future uncertainty. In a rural context, a growing population and an improving quality of the life might represent cases of uncertainty. Therefore, 'technology modularity' indicator aims to define how each alternative is capable of meeting a growing demand of fresh water.

The alternative that employs more modularized technologies is considered better.

The indicators *Improved other social services availability* and *Technology modularity* both evaluate if an alternative can offer other important benefits to the local community than provide the amount of freshwater set during the design phase of the desalination system.

Level of acceptability

Sub-Criterion: Social acceptability

Type: Qualitative

Description: The different alternatives employ technologies that can have different levels of acceptance depending on the local context. Social acceptability expresses the overview of opinions related to the desalination systems by the local population regarding the hypothesized realization of the project. It is extremely important since the opinion of the population and of pressure groups may heavily influence the amount of time needed to go ahead with and complete a rural desalination project. Social acceptance cannot be expressed as a measurable figure. The decision-maker has to evaluate the local social context in order to identify how each alternative can involve the local population and promote the ownership of the project. For instance, qualitative measures of alternatives towards the criterion can be obtained according to the results of surveys carried out in the local community.

The alternative that has favorable opinion in the local community is considered better.

3.3 Validation of the model

Section 3.2 described the application of the AHP model to the selection of the most appropriate desalination technology for a rural area, thus creating a tool that can be usefully used by non-technical decision-makers. In order to test and validate this tool, the hierarchy previously described is now applied to a real case of study that concerns a small-scale decentralized desalination plant, namely a brackish water reverse osmosis (BWRO) PV-driven plant built in the municipality of Amellou (Morocco). The aim is to verify if the decision to install this system was actually correct for the specific rural context.

The desalination system is a small-scale plant established and built by the Istituto Tecnòlogico de Canarias (ITC), conceived in the broader framework of the EU-funded ADIRA project that sought to demonstrate the feasibility of water desalination in water scarce rural areas around the Mediterranean Sea. The project ended in 2008 and detailed reports are available online [151]. The application of the AHP decision method to the case of study is carried out through the following steps:

- Description of the context
- Description of the BWRO PV-driven unit and of the appropriate alternatives
- Selection of the most appropriate criteria
- Pairwise comparisons
- Data processing and identification of the best alternative

3.3.1 Description of the context

The PV-RO unit is installed in the municipality of Amellou in the province of Tiznit. It provides with freshwater four small settlements located in the municipality, namely Arkha, Tioughza, Id Jamâa and Id Nakouss. Main activities are cattle farming, exploitation of natural resources, as prickly pears, and some agriculture limited by the scarce rain. Yearly average solar irradiation on horizontal plane is estimated about 5,9 $kWh/m^2/day$.

The approximate population served by the system is 300 inhabitants, divided in about 50 households. Therefore, the freshwater need is estimated to be around 6 m^3/day. The water fed to the system has a salt concentration of 2,900 ppm and it is pumped from a well by a pump driven by the PV system. The settlements have no access to the electric grid and the only communication route is a dirt road.

The rural municipality of Amellou was involved directly in the project, handling the civil works related to the construction of the system. A local association was in charge of managing the system and guaranties proper operation and maintenance, once the involved population has received an adequate training from ITC. Eventually, the system ownership was transferred from ITC to the rural municipality once the local partners were able to operate the system without external support.

It should be remarked that the ITC trained one member of the Amellou community to handle the basic maintenance, whereas staff of the Technical Department of the Tiznit Province was trained on the advanced maintenance.

Before the construction of the desalination plant, the water sources were the very scarce-rainfall and the groundwater extracted from an inland well. However, this water is usually contaminated and with a too high salt concentration. Cistern trucks may also reach the settlements; however, it is a very expensive solution.

3.3.2 Description of the alternatives

One of the results of the ADIRA project is the publication of the ADIRA handbook, where a brief review of the desalination technologies powered by RES can be found [152]. Through a market analysis, several techno-economical details are reported for each technology, thus providing an interesting database updated to 2008. Therefore, the alternatives to the PV-RO system are based on these data, so that it is possible to compare the real on-field data related to the installed system with estimated data related to other technologies, collected by the same authors and updated to the same year.

The alternatives to the selected system are a centralized system based on a humidification de-humidification cycle (HDH) and a decentralized system based on solar stills (SS), both of them able to provide the required amount of freshwater (6 m^3/day). Other viable alternatives like electrodyalisis and membrane distillation are not considered, since at the time when ADIRA project was carried out (2008), these technologies were at the basic stage of technical development and no reliable data were available.

3.3.2.1 Alternative A: PV-RO

The alternative actually implemented includes a PV-driven pump capable to extract the brackish water from a well and to feed the RO unit. The desalination system is mainly composed by:

- Physical and chemical pre-treatment
- Feed water storage tank
- Energy recovery system
- A solar evaporation pond, built near the plant, where the brine is collected

The BWRO is powered by a 4 kW photovoltaic system and the total area required is 180 m^2, which includes the evaporation pond (100 m^2), the desalination equipment building (56 m^2) and a small area for the location of external pipes. The PV panels are installed above the building's roof.

The capital cost and the WPC are reported to be equal to 90,000 € and 4.71 €/m³, respectively. Therefore, the specific capital cost results to be 15,000 €/m³day.

As for the established business model, the water production is centralized, each household consumes an equal share of the freshwater produced, paying a monthly quota. The occasional technical maintenance is provided by external technicians, whereas the local community is in charge of the unit cleaning and other basic operations.

3.3.2.2 Alternative B: solar-powered HDH

Since it was considered as one of the most promising technology for rural areas, HDH was studied and implemented within the ADIRA project and it can be selected as a possible alternative for Amellou case.

The considered HDH is a single-stage CAOW water-heated system, powered by evacuated tube solar collectors. The specific water production is 12 L/m²day, and the GOR is 3.5. The feed water extracted from the well is driven to the system by a PV-driven pump; hence, a small PV array is added to the solar collector field. The brine is disposed in a solar evaporation pond, larger than the one used by the RO due to the lower recovery ratio. The specific capital cost is calculated to be equal to 40,000 €/m³day, and the estimated lifetime is 20 years.

The business model is the same proposed for the BWRO. The maintenance can be provided by the local population, with occasional controls carried out by external technicians.

3.3.2.3 Alternative C: solar stills

As for the HDH cycle, solar stills were identified as an appropriate and well-proven technology for rural desalination within the ADIRA project and it can be selected as an appropriate alternative for this context. The current alternative considers a decentralized freshwater production, based on a conventional solar still, whose specific water production is 5 L/m²day and that have an area equal to 1 m^2.

In order to supply 6 m^3/day, 1,200 solar stills are needed, that means 24 devices for each household. Each household is in charge of the supervision and maintenance of its own devices; hence, there is no need of paying a monthly centralized quota. The brine disposal is managed by each household, by cleaning the salty leftover out the solar still's basin. The specific capital cost is estimated to be equal to 30,000 €/m³day, whereas the device's lifetime is expected to be approximately 10 years.

3.3.3 Selection of the most appropriate criteria

The hierarchy defined in section 3.2 comprehends a wide set of criteria, which might be not all relevant to the context where the method is applied and to the selected alternatives. Therefore, it is important to shape the hierarchy according to the specific case.

The hierarchy illustrated in figure 3.4 shows the general indicators scheme with deactivated indicators in red and crossed out.

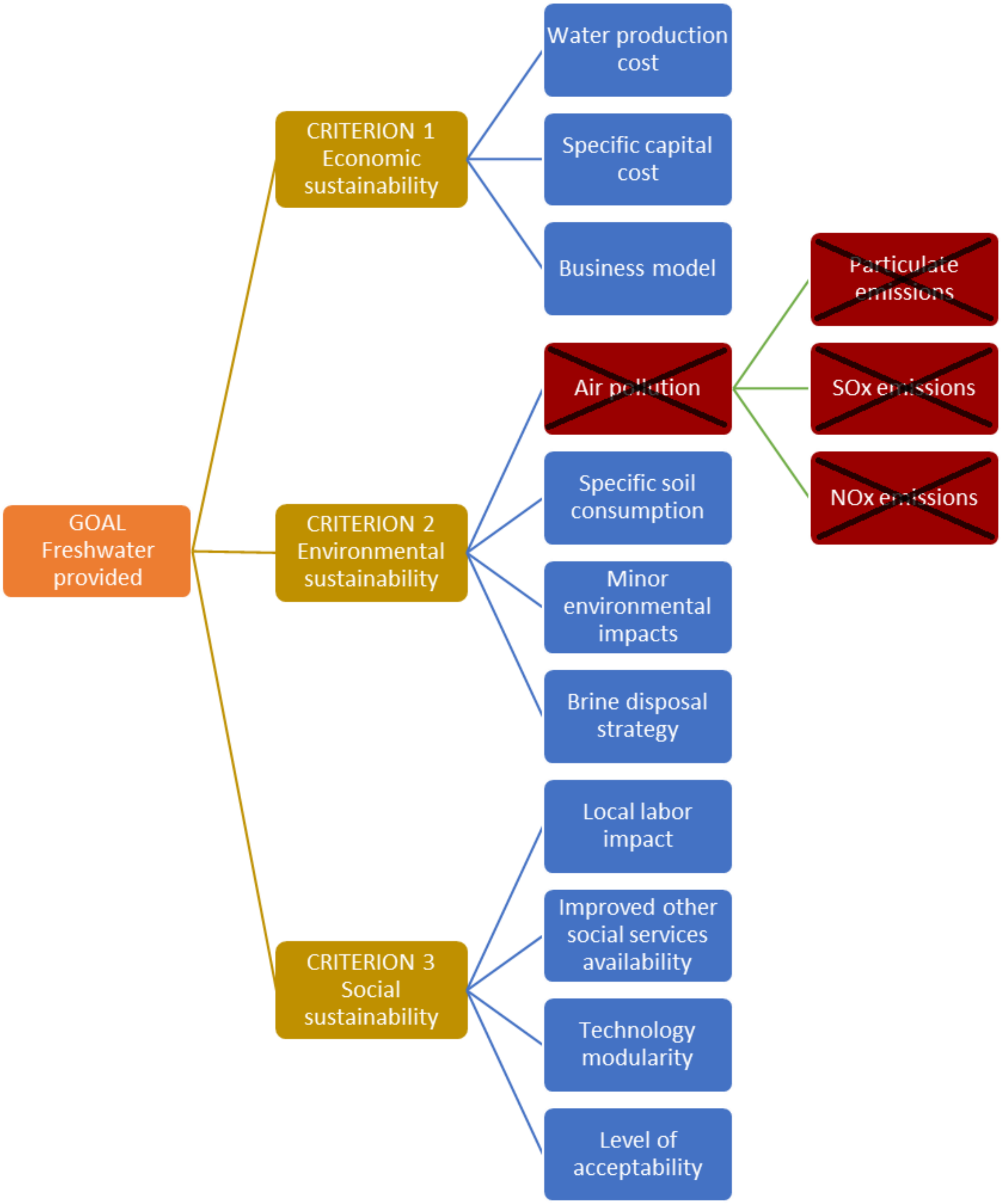


Figure 3.4: Scheme of the hierarchy for Amellou application

Compared with the general hierarchy reported in figure 3.3, the *Air pollution indicator* is not considered, since all the selected alternatives do not use conventional fuel and so they do not have any negative impact on the local atmosphere.

3.3.4 Comparison matrices

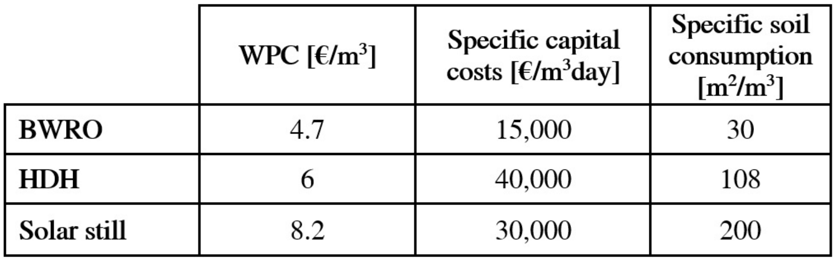
In order to find out which is the most appropriate alternative, it is necessary to make pairwise comparisons at each level of the hierarchy. These comparisons are based on the techno-economical data reported by the ADIRA handbook and on the socio-economical information presented in the project's report [151].

3.3.4.1 First level comparison

The comparison matrices related to the first level of the hierarchy are composed by the pairwise comparisons among the alternatives within each indicator. Therefore, it is crucial to gather the numerical values of all the quantitative indicators for each alternative, and to achieve a deep understanding of the local context, in order to be able to properly evaluate the qualitative indicators also.

Quantitative indicators

Table 3.2 reports the values of the quantitative indicator for each system obtained by the ADIRA handbook and completed with the data of the reviewed literature.



	WPC [€/m^3]	Specific capital costs [€/m^3day]	Specific soil consumption [m^2/m^3]
BWRO	4.7	15,000	30
HDH	6	40,000	108
Solar still	8.2	30,000	200

Table 3.2: Quantitative indicators for the three alternatives of Amellou application

It should be noted that the data regarding the PV-RO are the ones published in the report regarding the installation of the system, whereas the SS and HDH data were only estimated. In particular, the WPCs were calculated considering all the costs related to the system, such as capital cost, O&M and replacement. Moreover, the specific soil consumption of the HDH was estimated considering the area required by the solar collectors, the humidifier, the dehumidifier and the connected solar pond. The area required by the solar stills was directly calculated from the specific water production of the devices.

Qualitative indicators

The qualitative indicators are evaluated considering the local peculiarities and the technical features described in the critical review of the scientific literature on desalination processes (see chapter 2). The diagrams in figure 3.5 illustrate the priority of each alternative within each indicator.

Business model The four settlements of the Amellou municipality are slightly scattered; however, the presence of a local association implies a tight-knit community. Hence, a centralized production and the payment of a monthly fee seem to be the most appropriate solution. Although the solar still can be employed in a centralized model, HDH and PV-RO are obviously more suitable for this business model.

Brine disposal strategy A solar still produces a small amount of brine that needs only to be cleaned out by each household. A solar evaporation pond needs to be considered to discharge the brine produced by the HDH and the PV-RO units.

Minor local environmental impacts Due to the huge area required for the solar still installation, the visual impact of these devices has to be considered. The noise of the pumps operations associated to the HDH and RO processes might annoy the near households.

Local labor impact PV-RO and HDH need basic maintenance that can be provided by local manpower, after a proper training. The considered solar stills are not locally manufactured; hence, they do not create job opportunities.

Improved other services availability The electricity produced by the PV panels and stored in the battery storage of the RO unit can be used to feed other loads than the desalination unit. HDH collectors might supply the local community with a source of hot brackish water, useful for heating purposes.

Technology modularity PV-RO is characterized by the highest grade of modularity, since both the PV panels and the RO are modular and easy scalable technologies, thus availing system enlargement whenever needed. Adding solar collectors to the HDH can enhance its productivity. The freshwater production of the solar stills cannot be changed unless the whole system is replaced.

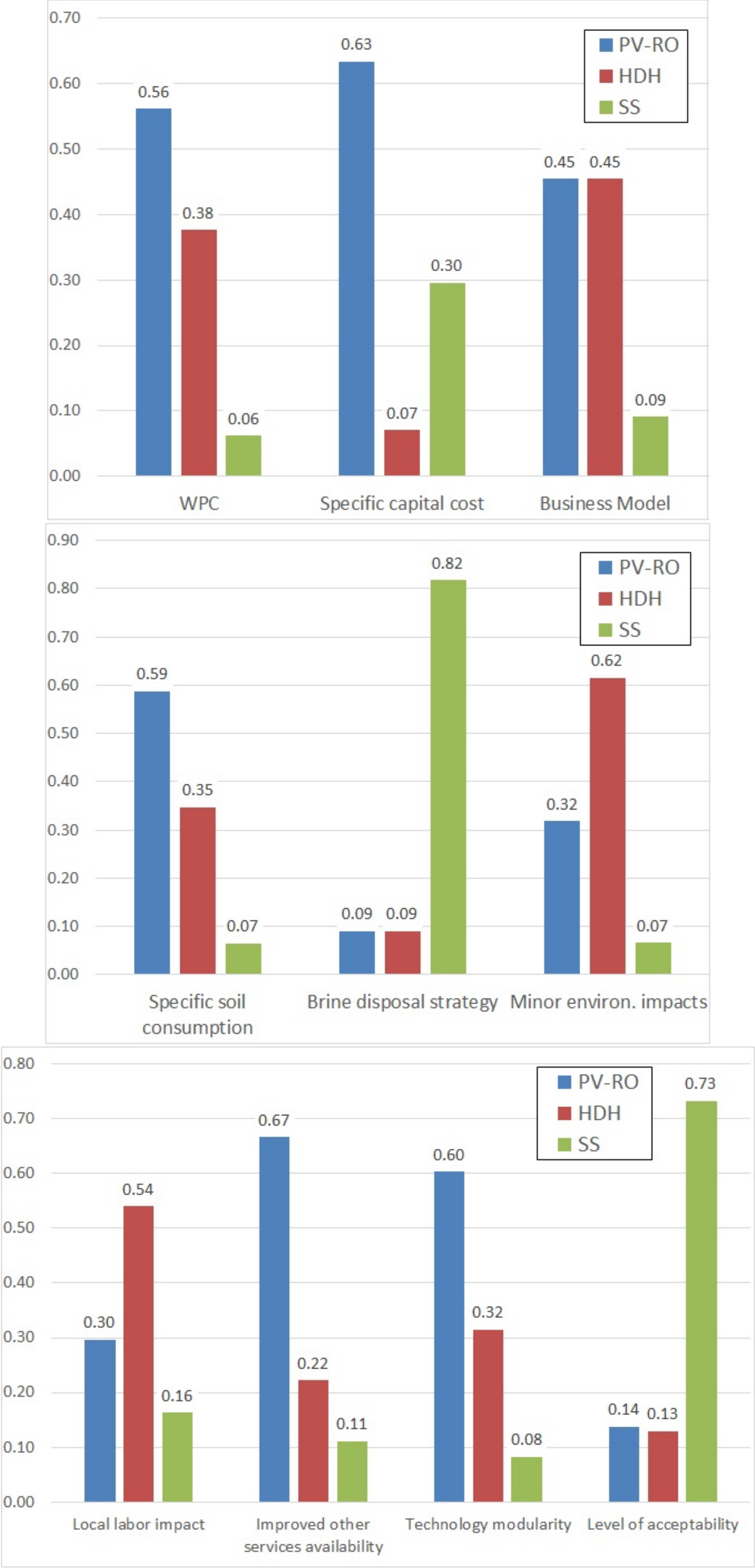


Figure 3.5: Diagrams of the priority of each alternative within the economic, environmental and social indicators

Level of acceptability According to the project's report, the PV-RO was actually well-accepted by the local community, and it is estimated that even the HDH would have the same level of acceptability. However, solar still alternative is estimated to be the most well-accepted solution, since an household-based management does not require the payment of a monthly fee. Moreover, give the responsibility for the solar stills to each household might enhance the people's ownership of the devices, thus increasing the acceptability of this alternative.

3.3.4.2 Second level comparison

The comparison matrices related to the second level of the hierarchy are composed by the pairwise comparisons among the indicators within the three main criteria. The resulting priority vectors reported in the diagrams in figures 3.6, 3.7 and 3.8 are composed by the weights of each indicator in respect to its related main criterion.

Economical sustainability The WPC is the indicator that considers all the costs occurred by an alternative; hence, it is a crucial parameter for evaluating the economical performance of an alternative. However, it should be noted that the WPC is not indicative of the price that the local population has to pay for the water service, which depends on the project's policies and on the established business model. The specific capital cost is an important parameter due to the project limited budget. On the other hand, the economical sustainability of the alternative over the years is guaranteed by the business model, which is a very important indicator. Therefore, all the three indicators are considered to have the same importance towards the economical sustainability (see figure 3.6).

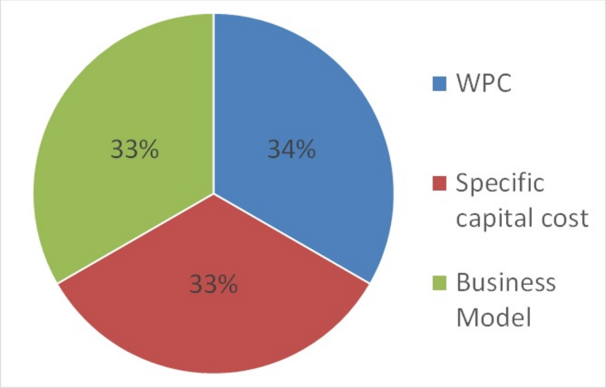


Figure 3.6: Diagram of the priority of the economic indicators within the economic sustainability criterion

Environmental sustainability The specific soil consumption is considered the most relevant environmental indicator, since the area required by an alternative is in competition with other land usages such as farming and cattle breeding. The brine disposal cannot be underestimated, since it can be harmful for the local environment if not properly treated. The minor environmental impacts do not have a great impact on the local context. The importance of the three indicators towards the economical sustainability criterion is shown in figure 3.7.

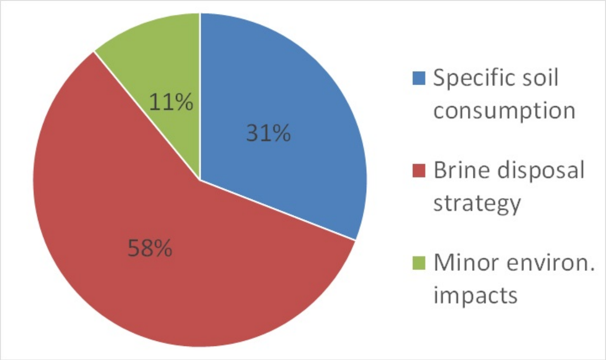


Figure 3.7: Diagram of the priority of the environmental indicators within the environmental sustainability criterion

Social sustainability The level of acceptability is estimated to be the most important indicator, since it expresses the overview of opinions related to the desalination system by the local population regarding the hypothesized realization of the project. The technology modularity is also a valuable indicator, since a growing demand of water will likely occur. The local labor impact and the improved other services availability indicators are considered to be less-relevant, because all the three alternatives do not create many jobs opportunity, and the opportunity to employ the HDH's hot water or the electricity of the RO PV system is not a major concern. The importance of the three indicators towards the economical sustainability criterion is shown in figure 3.8.

3.3.4.3 Third level comparison

As it was underlined in sections 1.1 and 3.2, a full sustainability is reached only if the project addresses the economical, environmental and social dimensions at the same time. Therefore, these three main criteria have the same relevance respect to the goal. Hence the same weight is assigned to each criterion. Figure 3.9 shows the resulting priorities.

3.3.5 Results and sensitivity analysis

As a result of the processing of all the priority vectors, the global priority vector is obtained. Figure 3.10 reports the score of each alternative towards each main criterion, calculated by handling all the priority vectors values of the lower levels.

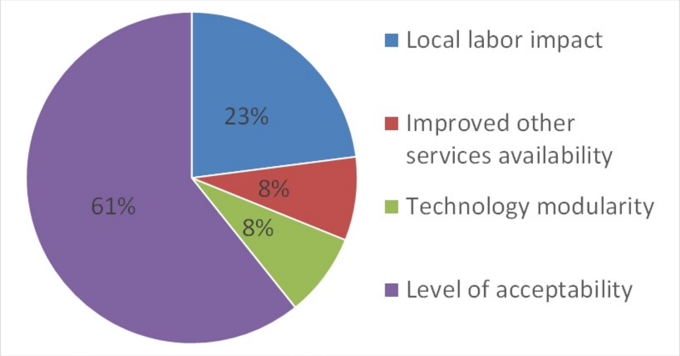


Figure 3.8: Diagram of the priority of the social indicators within the social sustainability criterion

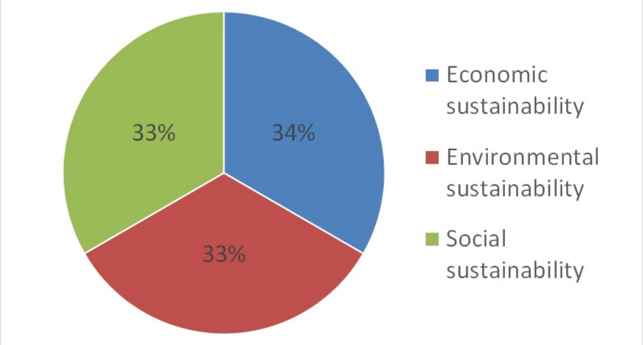


Figure 3.9: Diagram of the priority of the three main criteria within the goal

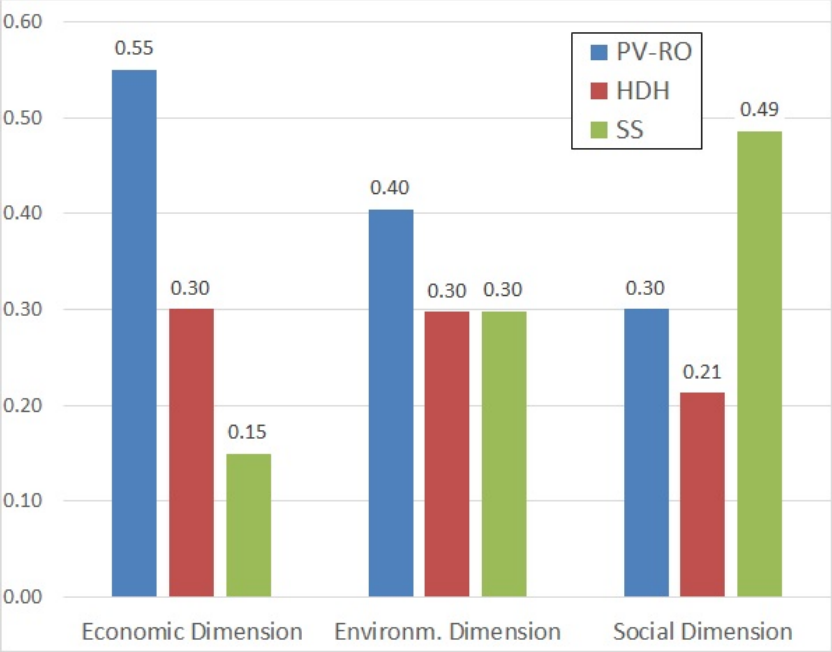


Figure 3.10: Diagram of the priority of each alternative within the three main criteria

These scores are processed again to calculate the global priority vector, reported in figure 3.11. The global priority vector gives the ranking of the alternatives.

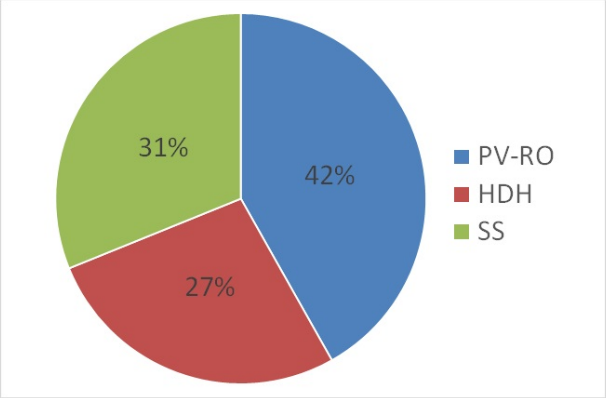


Figure 3.11: Diagram of the global priorities of each alternative within the goal

The most appropriate solution results to be the PV-RO, already selected by the ITC. However, since the AHP method is affected by the subjectivity of the decision-makers, it is essential to verify that small changes of the decision-makers opinion do not lead to a different ranking of the alternatives. In order to find out the range where the solution does not change due to a variation of a criterion weight, a sensitivity analysis was performed employing the sensitivity analysis tool in the *Super Decision* software.

The priorities of each alternative towards the indicators are directly related to their own technical features; hence, they are not affected by the subjectivity of the decision-makers. Moreover, there is no reason to develop a sensitivity analysis on the main criteria weights, since the desalination solutions must be designed considering equally all the three dimensions of the sustainability. Therefore, the sensitivity analysis was carried out only on the weights of each indicator in respect to its related main criteria. These weights are deeply affected by the opinions of the local stakeholders and by the subjectivity of the decision-makers. It resulted that the ranking of the alternatives does not change for any variation of each weight, except for the two reported in figure 3.12.

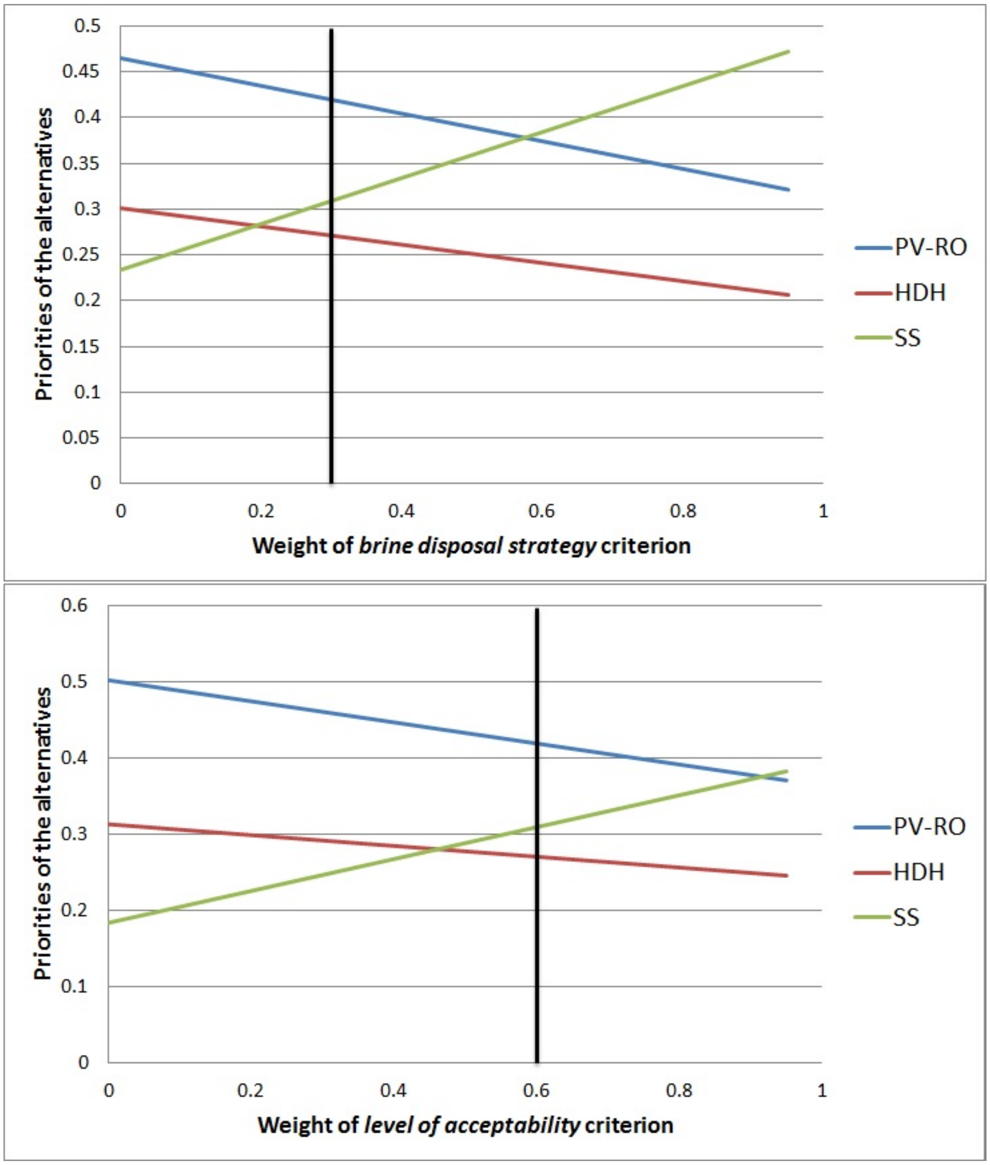


Figure 3.12: Sensitivity analysis of the brine disposal strategy and social acceptability

The vertical line marked in black stands for the value of the criteria weight before the sensitivity analysis.

It should be noted that it is necessary to grow the weights of the *brine disposal strategy* criterion and *level of acceptability* criterion by the 100% and 50% respectively, in order to change the ranking of the alternatives. Therefore, it is possible to state that the resulting scores of alternatives would have been about the same even though the qualitative pairwise comparison matrices had been drawn up by real decision-makers, assuming that they made assumptions not too different from those applied by the authors.

Eventually, it is important to underline that the relevance of an alternative towards an indicator depends on its technical-economical figures, which are strongly affected by the local context. Considering the illustrative case of the solar still, it is sometimes possible to use manpower and local materials for its construction, thus leading to a significant reduction of its costs. As a matter of facts, a possible reduction of the capital cost by the 50% leads to a change in the ranking of the alternatives, as it is reported in figure 3.13.

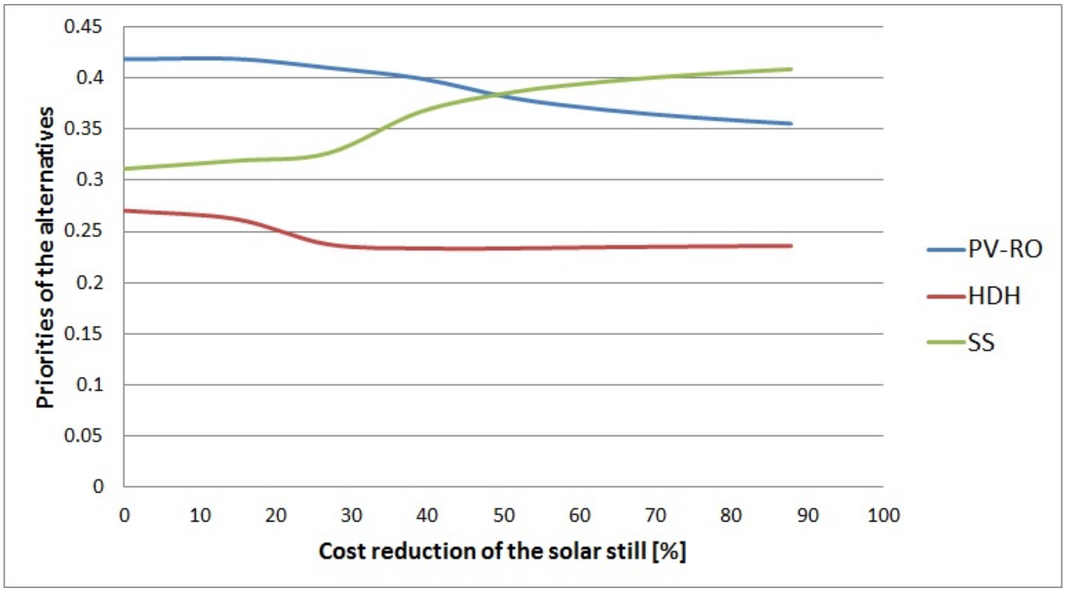


Figure 3.13: Sensitivity analysis of the solar stills WPC

3.3.6 Conclusions

The most appropriate solution results to be the PV-RO: the decision method agrees with the choice made by the ITC. Since the decision method agrees with the choice made by a team of technical experts on desalination, this test in considered to be positive. As a matter of facts, the decision method is conceived for being a useful tool for non-technical decision-makers; hence, if the method is in accordance with the decision made by experts of the desalination field, a non-technical decision-maker employing it will be able to select the most proper desalination system, without having a deep knowledge of the technologies. It should be noted that the role of the stakeholders in the weighting of the criteria is essential.

Further tests, especially on more recent projects and on different contexts, are needed to understand the strengths and weaknesses of the method and thus to reach a complete validation.

Chapter 4

RES for desalination: the AUC research project

In chapter 3, an AHP model was developed to support the decision-maker in the selection of the most appropriate desalination technology for a given rural context. Once the solution is selected, it is necessary to properly design the desalination system. In particular, in membrane desalination, the design of the renewable energy systems (RES) committed to power the unit is crucial. De facto, as it was stated in chapter 2, the main drawback of a RES-powered membrane technology is the high capital cost of the energy system.

As an example of a real case application, the present chapter reports the selection and design of a RES powering a research facility focused on membrane desalination technologies, at the American University in Cairo (AUC).

The study belongs to the wide framework of the EU-funded '*Knowledge-Triangle Platform for the Water-Energy-Food Nexus in Egypt*'. According to its website, the Trinex project is [153]:

> "A multidisciplinary project aimed at addressing the deep-rooted research and innovation vacuum in Egypt. With its emphasis on the importance of the Water-Energy-Food (WEF) Nexus as the launching pad for Egypt's development, it will provide a unique and vital boost to Egypt's ailing research establishment with particular focus on Egypt's looming security difficulties"

The AUC's Center for Sustainable Development (CSD) and the Energy Department of Politecnico di Milano are together involved in the TriNex project.

Context

AUC is the region's premier English-language University and an essential contributor to the social, political and cultural life of the Arab world. It involves more than 6,000 students and

500 faculties and, in September 2008, it moved the bulk of its operation to a a 260-acre campus in the developing desert city of New Cairo.

The CSD was established to help the university and Egypt to face the challenges of sustainability, by connecting all of the AUC departments and research bodies to develop innovative and achievable green solutions. Water management is one of the main concerns of the center; thus, a research facility on desalination technologies has been recently established and the Politecnico di Milano was asked to give support for the choice and the design of the energy system to be implemented.

In the present chapter, the selection of the most appropriate RES system able to power the facility and the detailed design of the selected RES are showed.

4.1 Selection of the RES

The present section describes the following subjects:

- Load evaluation: the desalination laboratory is analyzed enlightening the power and energy requirement of the installed equipment.
- Energy assessment: the goal of the RES is to power the desalination laboratory in a sustainable way, thus the analysis of the local natural resources is required.
- Numerical simulation: several scenarios based on the load evaluation and on the energy assessment are developed in order to identify the most appropriate RES configuration
- Selection: the identification of the most appropriate RES powering the desalination facility is carried out.

Figure 4.1 shows the process flow chart of the RES selection.

4.1.1 Load evaluation

4.1.1.1 Context analysis

The aim of the research facility on desalination technologies is to study innovative solutions for raw water treatment and for the production of freshwater.

The facility will enable the CSD's staff to perform experiments on membrane desalination systems such as brackish water and seawater reverse osmosis, nano-filtration and forward osmosis. In addition, the laboratory is part of a broader research project focused on the nexus between energy, water and food, thus it will be connected to innovative agriculture and energy systems. As a matter of facts, in the next months the installation of an aquaculture facility, a RES system and a biomass digester are planned.

The research facility's energy requirement can be separated into electricity requirement – mainly due to the desalination equipment – and thermal requirement - needed for heating and

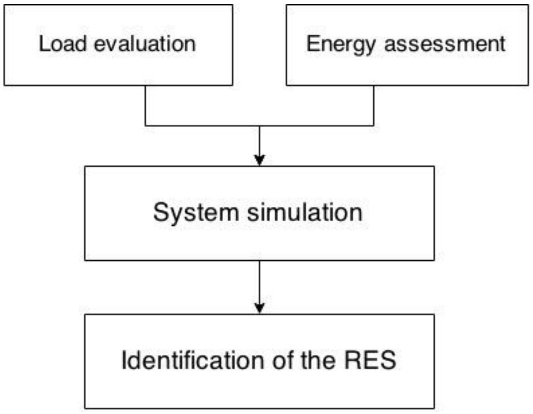


Figure 4.1: RES selection process flow chart

cooling the building. The study is mainly based on the examination of the equipment's data sheets and on thermal simulations. A deep understanding of the functioning of the laboratory was achieved through joint meetings with the laboratory's staff members and the desalination equipment's suppliers.

The following paragraphs report a brief description of the lab's location and building, since those parameters have a great influence on the energy requirement.

Location

The laboratory is located inside the AUC's campus in New Cairo (Latitude 30°00'N; Longitude 31°47'E). New Cairo lies on the east of Cairo city, on the boarder between the city and the desert. The facility is freely exposed to south and west, whereas it faces two higher buildings at north and at east. The orientation is the preferable for catching the solar radiation; whereas, the surrounding buildings cast their shadow over the desalination laboratory, especially during the summer season.

The prevalent wind direction in Cairo Governorate is north/north-east; thus, the laboratory is shielded by the surrounding buildings from undisturbed wind for almost all the year.

Building

The one-floor building is divided in two zones (see figure 4.2): a small office ($\approx 7m^2$) and a desalination equipment room ($\approx 69.5m^2$); the two zones are communicating by a door and a glass window. The walls are composed by a fixed temper glass covered by a wooden framework; the share of windows area over the total wall area is about 14%. The roof and the floor are instead made of concrete ($\approx 83.5m^2$), and the only access is located on the west side of the building (see figure 4.3). The roof is covered by an insulating liquid layer, enclosed by a semi-rigid plastic cloth.

Figure 4.2: South-west view of the desalination laboratory

Construction progress

When the present study was carried on, the building was erected and almost all the equipment was installed. The staff of the *International desalination & water treatment LLC* company was still working on the system and the equipment was not running. Therefore, actual measurements of the effective power consumption of the equipment could not be taken. The air conditioning system, composed by three reversible split units, was already running.

4.1.1.2 Electrical requirement

Four different membrane desalination processes are going to be tested in the laboratory. Therefore, the facility consists in a complex layout of valves, pipes, pumps and membranes.

Figure 4.4 reports a streamlined layout of the system. The raw water is pumped from a storage tank to the chemical pretreatment system by the *CRT 8-3* pump. The chemical system filters and changes the composition of the raw water via the dosing pumps *EMP KKS* and *EMP 2*, according to the test that has to be performed. Then, raw water flow can follow four different loops:

1. Seawater Reverse Osmosis loop. The salt water is fed to the seawater reverse osmosis membrane via the *APP1/APM 08* pump that includes an energy recovery system. High pressure is required by the high salt concentration, whereas an axial piston motor (APM) is used to transfer the energy of the brine stream directly into the new stream. Afterward,

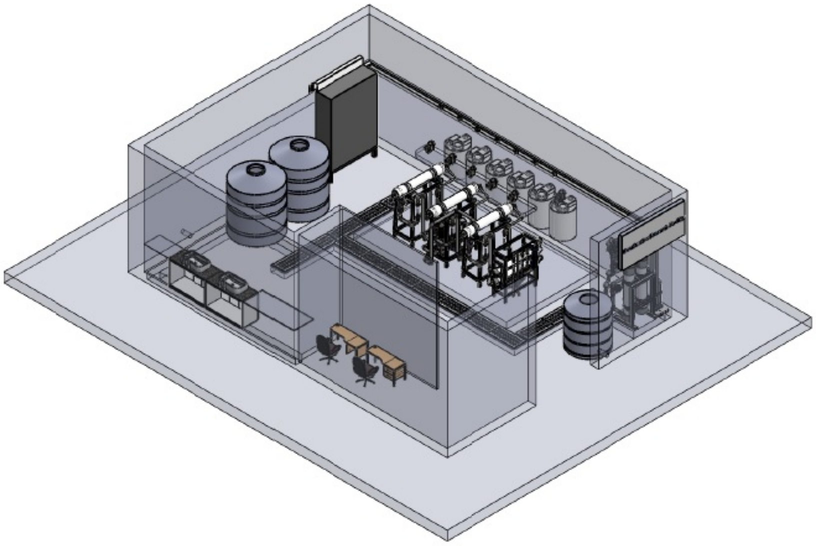


Figure 4.3: 3D layout of the desalination laboratory

both the brine stream and the freshwater[1] are gathered in the *water storage #1*, where the two flows get mixed, in order to restore the initial chemical composition. Finally, the mixed flow is fed again to the *APP1/APM08*, thus closing the loop.

2. Nano-filtration loop. The feed water is pumped by the *CRT 2-5* pump, which forces the treated water to the nano-filtration unit. Finally, both the brine stream and the freshwater flow are collected in the *water storage #1* and they are re-circulated, just like the seawater loop.
3. Brackish Reverse Osmosis loop. The salt water is driven by the *CRN 10-4* pump to the brackish reverse osmosis membrane. The brackish RO loop is alike the seawater one, with the remarkable difference that the pressure in the first case is strongly lower than in in the latter and that the two outgoing flows are collected in different tanks.
4. Forward Osmosis loop. This particular type of process needs two water flows. The first is the draw water flow that needs to be purified: this flow is driven by the *CRT 2-5 pump*. The second flow is forced by the *CRN 10-4* into the forward osmosis membrane, thus becoming the brine flow. Afterward, both the brine and the freshwater flows are collected in the *water storage #1*, and they can be recirculated after a proper chemical treatment.

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[1] marked in red and in blue, respectively

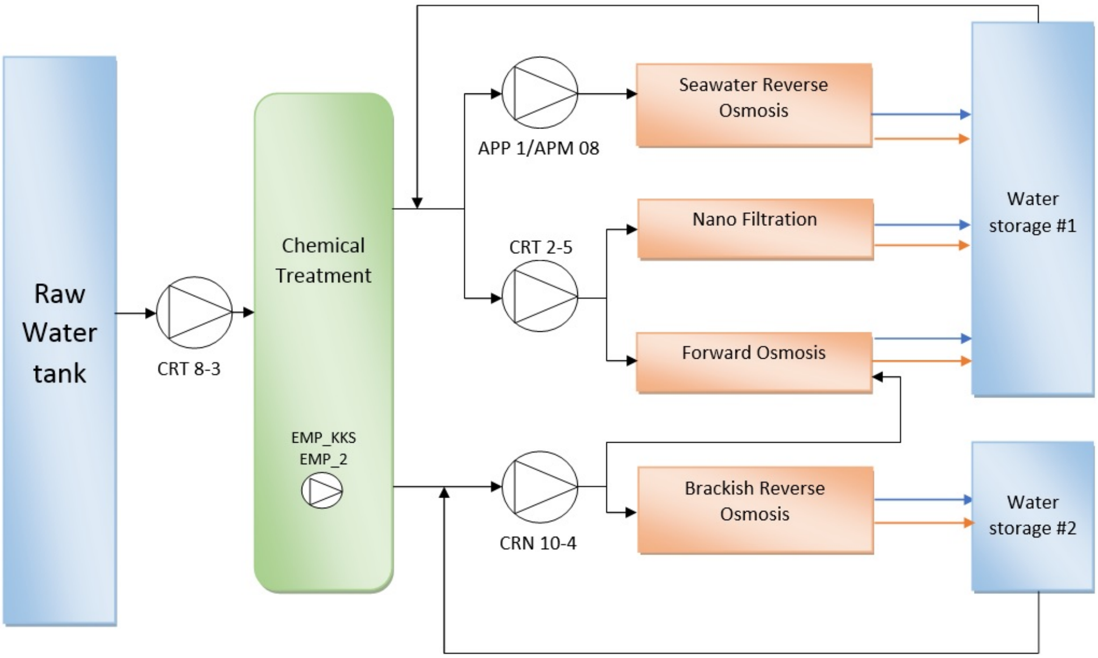

Figure 4.4: Water loops of the desalination laboratory

Table 4.1 provides a summary of the main technical data of the pumps installed in the facility.

	Function	Rated Power [W]	Rated Flow [m^3/h]	Rated pressure [bar]
EMP KSS + EMP 2	Dosing	106	< 0.001	-
CRT 8-3	Feed water circulation	1,100	9.5	2.4
CRN 10-4	Brackish/Forward	1,500	10	3.1
CRT 2-5	Nano/Forward	550	2.5	3
APP 1 / AMP 0.8	Seawater	2,200	1.05	20-80

Table 4.1: Rated characteristics of the pumps of the desalination laboratory

The *APP1/APM 0.8* is a volumetric pump; hence, the datasheet reports a minimum and a maximum pressure instead of a rated single one.

The pumps make up the main electrical load of the facility. Other loads include the lighting system, the measurement equipment and small office devices like laptops. The total amount of power required by these devices it is expected to not exceed 400 W.

4.1.1.3 Thermal requirement

The data sheets of the four *Hydranautics* membranes report the same limitation in the maximum operating temperature, setting it at 45°C. However, the sheets specify that all the reported limitations may be more conservative for specific projects, in order to ensure the best performance and longest life of the membranes. Therefore, a deep discussion with the laboratory's suppliers on the peculiarities of the project was needed in order to identify the appropriate temperature of the facility's indoor air throughout the year.

In Cairo Governorate the air temperature can reach 40°C during midday hours in August and it can drop below 5°C during night time in January. Moreover, during the Winter season the temperature difference between night and day hours can reach 20°C. The performance of the four desalination membranes can be largely affected by the great temperature difference during the day and among the year. Therefore, as it emerged from the discussion with the suppliers, the air temperature of the desalination equipment room should be kept between 20°C and 22°C.

Dynamic thermal simulation In order to evaluate the thermal load of the facility along the year, simulations based on an actual set of conditions related to the desalination laboratory were performed using a free trial version of *DesignBuilder* (v4.2). *DesignBuilder* is a comprehensive user interface to the *EnergyPlus* dynamic thermal simulation engine. *EnergyPlus* is a stand-alone simulation program - without a 'user friendly' graphical interface - that models heating, cooling, lighting, ventilation, other energy flows and water use. Therefore, it represents a useful software for complex and problematic projects. Some of the included capabilities (such as hourly time-steps, multizone air flows, photovoltaic systems, shadowing analysis) led up to choose *EnergyPlus* – integrated with the *DesignBuilder* environment – as the most appropriate thermal simulation program for the present study.

DesignBuilder uses *EnergyPlus* format hourly weather data to define external conditions during simulations. Each location has a separate file describing the external temperature, solar radiation, atmospheric conditions etc. for every hour of the year. As it will explain in subsection 4.1.2.1, since hourly weather data were not available for the involved location, it was necessary to use weather data for a nearby location. In particular, the dataset from the Egyptian Meteorological Station was chosen in order to use data that represent the weather of the actual site as much as possible.

The 3D model of the desalination laboratory and the surrounding buildings was first created tracing block perimeters and partitions from a 2D technical drawing of the involved area. Among all the input parameters, the activities of the two different zones of the building and their related comfort data had to be defined selecting them from the activity template list of *DesignBuilder*:

- A 'Generic office area' was selected for the office zone. Therefore, the workday profile considers an occupancy from 7 am to 19 am, five-day week. The Heating Setpoint Temperature was set at 20°C, while the Cooling Setpoint Temperature at 24°C.

- A '24x7 Warehouse Storage' was selected for the desalination equipment room. The workday profile considers an occupancy from 0 am to 24 pm, seven-day week. In accordance with the suppliers' guidelines, the Heating Setpoint Temperature was set at 20°C and the Cooling Setpoint Temperature at 22°C.

EnergyPlus thermal simulations were then performed for the desalination building, considering its interaction with the surrounding buildings, in particular the shadowing effect. The results report yearly, monthly and hourly data about plenty of characteristics as the temperature distribution, the building utility performance and energy consumption, etc. Figure 4.6 reports the monthly thermal requirement calculated for a standard year.

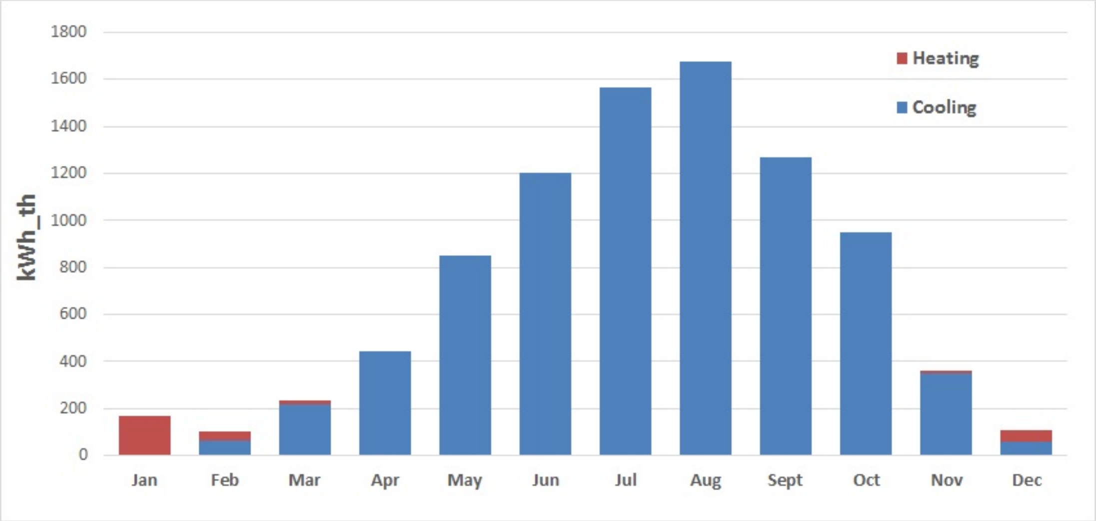

Figure 4.5: Thermal requirement during a standard year

The thermal load is provided by three reversible split units, powered by electrical energy. Therefore, the thermal requirement has to be converted to an electric load, through the coefficient of performance (COP) of the air conditioning units.

The rated coefficient of performance (COP) of the units is 2.9 for the heating mode and 2.8 for the cooling mode. Although the performance of the devices can be estimated more precisely using the seasonal COP (SCOP), a constant COP equal to 2.8 was assumed for both heating and cooling mode, since the SCOP was not available. This is a conservative assumption, since the employment of the seasonal COP leads to an higher estimation of the air conditioning unit performance.

Thanks to the COP of the three heat pumps, it is possible to calculate the electrical energy required to satisfy the thermal requirement of the building.

4.1.1.4 Load profile

Figure 4.6 shows the average load profile for two different months: February and August. These profiles are made up by the sum of the electrical load and the thermal requirement[2]. The reported load profiles are calculated for the worst-case scenario, i.e. considering all the equipment switched on and working at the rated power for eight hours each workday. It was decided to design the PV system on the worst-case scenario, in order to guarantee the operation of the laboratory even at full load.

The average daily electrical energy consumption of the research facility is 42.3 kWh. The highest power peak load is expected to occur in August, due to the high electrical requirement of the cooling system, and it will be equal to 7.2 kW, divided in cooling load, pumps load and other loads as shown in figure 4.7; it should be noted that the electric load of the pumps, marked in red, is the highest. Whereas the minimum will happen during February, since the heat and cool demand will be the lowest (see figure 4.5).

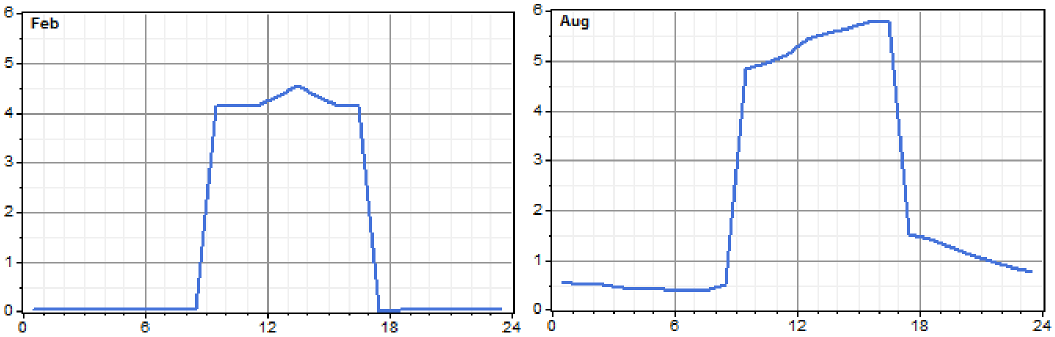

Figure 4.6: Expected load profiles during February and August [kWh]

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[2] converted in electrical consumption of the air conditioning system

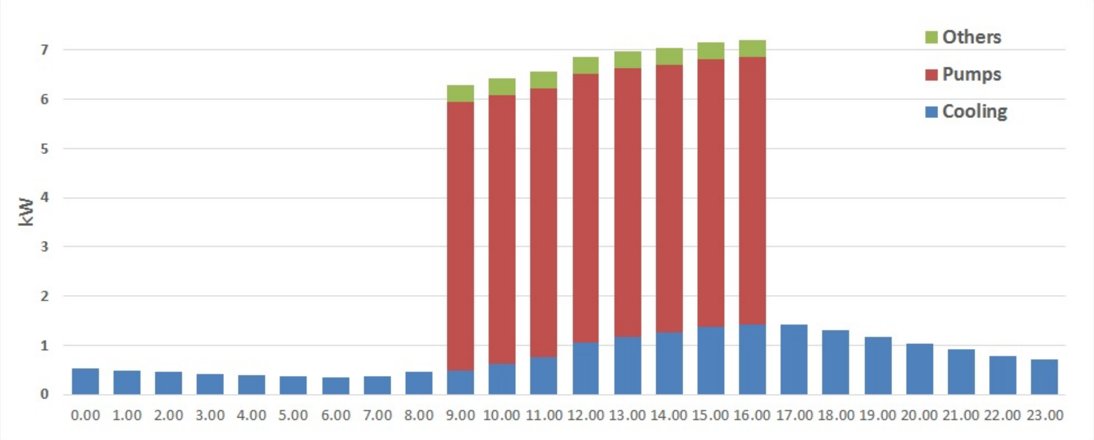


Figure 4.7: Expected load profile during the 15th of August

4.1.2 Energy assessment

The aim of the RES system is feeding the desalination laboratory load using as much as possible the most promising natural resources already available at the AUC campus. Thus, the current assessment takes into account the solar resource - abundant in Egypt -, the inland wind resource - a currently focus of the Egyptian government - and the biomass resource - largely available in different forms as organic waste.

RES are strongly related to the local context. A traditional power system can supply the same amount of energy in several different contexts, whereas the one produced by a RES is strongly affected by multiple local factors, such as weather conditions, pollution, orography etc. Therefore, a deep understanding of the local environment is essential in order to design a RES.

4.1.2.1 Solar energy assessment

Solar radiation is universally available at any location, generally with higher values closer to the Equator. However, the radiation that reaches the surface of the earth is only a portion of the solar radiation received at the periphery of the atmosphere. The solar radiation going through the atmosphere is partially absorbed by its constituents, partially reflected back to space and partially diffused, with the remaining reaching the ground as direct solar radiation [154].

In addition to the absorption and diffusion of solar radiation by the usual constituents of the atmosphere, two additional attenuation mechanisms take place in a real atmosphere, namely the absorption by water vapor and the scattering by aerosol particles. The additional attenuation caused by these two processes is known to be due to the turbidity of the atmosphere [155, 156]. Hence, one of the most important factors affecting the amount of solar irradiance reaching the earth's surface is the urbanization and the industrialization processes [154]. The Greater Cairo region, in which the desalination laboratory is located, lies south of the Nile delta. It is characterized by the presence of Moqattam hills to its east and southeast and of desert areas extending in the west and east directions. The rapid increase in population, large industrial areas, many traffic jams and commercial activities have resulted in high air pollution levels during the last several years. The concentration of suspended particulate matter increases approaching the city and – together with the dust particles coming from the surrounding deserts and from the Moqattam hills – it increases the opacity of the sky, leading to a sensible reduction in the global solar radiation that reaches the surface of the region [154, 156, 157].

Effects of the urbanization on the solar radiation over Cairo In order to investigate the effect of urbanization processes on the global solar radiation values (G) received at the urban area of Cairo, Robaa [157] compared the monthly mean values of G for the non-urbanized period (1969–1973) with the corresponding values of the recent heavily urbanized period (1999–2003), both measured at the same meteorological station. The monthly and seasonal mean values of G for the two periods with the percentage reduction, E%, are shown in figure 4.8.

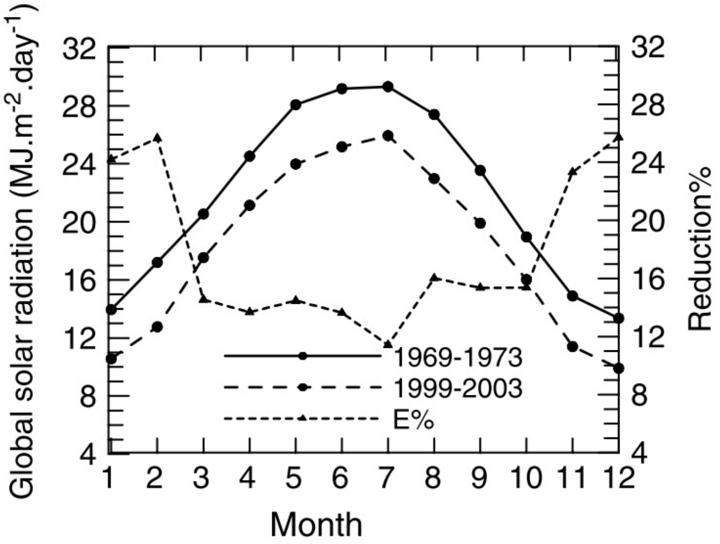


Figure 4.8: Monthly variation of G during the non-urbanized period (1969–1973) and the urbanized period (1999–2003) and the calculated percentage reduction of G during the urbanized period at the Cairo urban area [157]

It can be noticed that the radiation values of the non-urbanized period are always higher than those found in the recent, urbanized period throughout the year. This is ascribed to the serious combined effects of the recent, increased atmospheric pollution because of increased population, urbanization and industrialization [157]. Moreover, the subtropical and semi-arid climate exacerbates the pollution effect: rainfall in Cairo is generally low throughout the year, preventing the possibility of ‘washing’ the atmosphere; sandstorms frequently blow during spring and autumn, always associated with hot and dry winds blowing from north/north-west, causing rapid transportation of the dust from the adjacent desert and thus increasing the atmospheric pollution.

Other on-field studies, comparing solar radiation data measured at different locations in Cairo and in other regions, point out the same conclusion: the rapid increase of urbanization processes in Cairo area is depriving Cairo of the solar energy [154, 155, 156, 158].

The following paragraph aims to describe the course of evaluation of the available radiation data that led to the choice of the solar radiation values to be used for the RES design.

Review and evaluation of the available solar radiation data In order to consider the effects of the local environmental factors on the solar radiation reaching the ground, actual measurements of the radiation are needed for the specific location. Unfortunately, for many developing countries like Egypt, solar radiation measurements are not easily available due to the cost of maintenance and calibration requirements of the measuring equipment. Therefore, although Egypt is a vast country, there are only few meteorological stations that measure the solar radiation components [159].

To overcome this situation, in the last years several empirical models have been developed to calculate global solar radiation using various available parameters, such as extraterrestrial radiation, sunshine hours, altitude, latitude etc. Consequently, nowadays a number of studies and databases are available in order to obtain a first estimation of the annual radiation that reaches a selected location [159, 160]. Although these sources provide data with global or continental coverage, their spatial resolution is often relative coarse (1x1° for the NASA SSE, 40x40 km for the data from NREL). This coarse spatial resolution might lead to anomalous predictions. Therefore, for the current study Photovoltaic Geographical Information System (*PVGIS*) free database was chosen to obtain a first estimation of the solar radiation that reaches AUC campus. Thanks to its 2-km spatial grid resolution, PVGIS provides a high-resolution map-based inventory of solar energy resource (representing the period 1985-2004) [161, 162, 163].

One year of hourly measurements of the solar radiation were also available for the location thanks to a weather station installed at the campus. Solar and wind data were recorded from December 2011 to November 2012 by the *Rain Bird WSPRO LT* weather station installed on the rooftop of the Research Institute for a Sustainable Environment (*RISE*) building. In particular, hourly values of global horizontal radiation were measured by the station solar pyranometer.

Thanks to a proper elaboration of the measurements, the monthly-average daily radiation values were calculated and compared with the one obtained from PVGIS for the location (30°00’N; 31°30’E). As it is clearly shown in figure 4.9, AUC station measurements lead up to

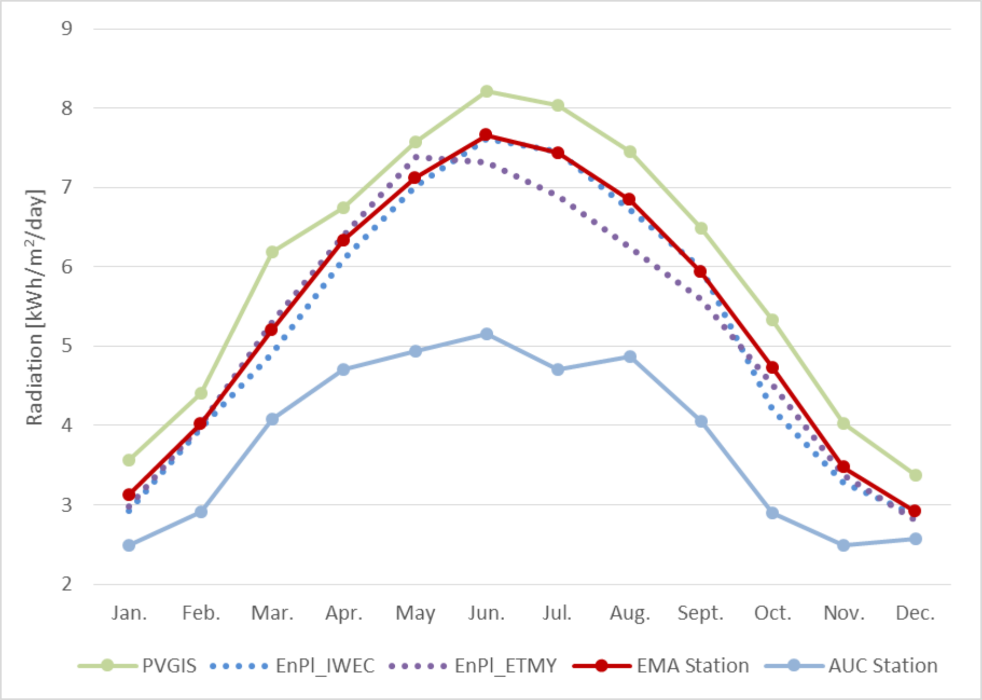


Figure 4.9: Monthly-average daily radiation reported by the analyzed datasets

substantially lower values than the PVGIS estimations. As some meetings with the RISE staff revealed, no maintenance and cleaning of the pyranometer were performed after the installation of the weather station. However, as previously mentioned, reliable solar measurements require constant maintenance and cleaning of the equipment, especially in a high-polluted and sandy region like Cairo Governorate. Therefore, the on-campus measurements cannot be considered reliable and they cannot be used for the evaluation of the local solar radiation.

Solar data from nearby weather stations were then considered in order to identify the most reliable and representative ones. First, the commonly-used online database by EnergyPlus was analyzed [164]. Two datasets from the Cairo International Airport station are available online: one of them reports only predicted solar radiation values and the other one reports anomalous measured data without any description of the measuring equipment (see *EnPl_IWEC* and *EnPl_ETMY* lines in figure 4.9). It was therefore decided to avoid the use of these two datasets.

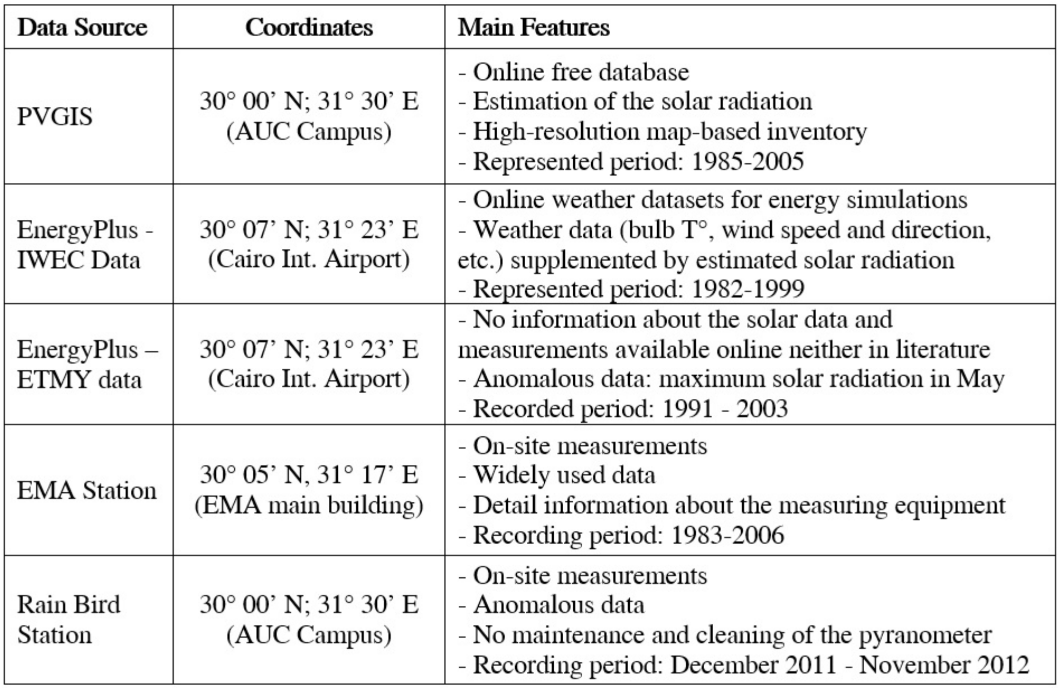
The available scientific literature was then analyzed. Several studies on the characteristics of the solar radiation over Cairo take advantage of solar data measured at the main building of the Egyptian Meteorological Authority (*EMA*) headquarter [154, 155, 156, 157, 158, 159, 164, 165, 166]. The EMA station is part of the solar radiation network station in Egypt that consists of 10 stations. The network started measuring global radiation in 1969 in four stations including the EMA one [167]. In particular, Robaa [154, 157] and Zakey et al. [167] report detail information on the measuring equipment used for collecting data at the EMA building, guaranteeing a yearly calibration of the pyranometer and specifying that the accuracy of the instrument corresponds to the first class accuracy according to the World Meteorological Organization classification.

De facto, the EMA set of data is the most reliable set that could be found among the available sources. In particular, it was decided to use the monthly mean values of global radiation measured in the period 1983-2006 at the EMA building and reported by Robaa [159] for the designing of the RES (see *EMA Station* line in figure 4.9).

As previously mentioned, AUC campus lies on the border of the desert thus experiencing a sandy atmosphere, whereas EMA headquarter is located in the very high-polluted area of Central Cairo (see figure 4.10). As shown by Diabete et al. [155], the pollution that characterizes the city has generally a greater effect on the attenuation of the solar radiation than the desert dust blowed by the wind; hence, the choice of the EMA station data is considered conservative.

A proper on-site measurement campaign would be needed in order to get more accurate data on the solar radiation that reaches the campus.

Table 4.2 summarizes the main features of the analyzed solar datasets.



Data Source	Coordinates	Main Features
PVGIS	30° 00' N; 31° 30' E (AUC Campus)	- Online free database - Estimation of the solar radiation - High-resolution map-based inventory - Represented period: 1985-2005
EnergyPlus - IWEC Data	30° 07' N; 31° 23' E (Cairo Int. Airport)	- Online weather datasets for energy simulations - Weather data (bulb T°, wind speed and direction, etc.) supplemented by estimated solar radiation - Represented period: 1982-1999
EnergyPlus – ETMY data	30° 07' N; 31° 23' E (Cairo Int. Airport)	- No information about the solar data and measurements available online neither in literature - Anomalous data: maximum solar radiation in May - Recorded period: 1991 - 2003
EMA Station	30° 05' N, 31° 17' E (EMA main building)	- On-site measurements - Widely used data - Detail information about the measuring equipment - Recording period: 1983-2006
Rain Bird Station	30° 00' N; 31° 30' E (AUC Campus)	- On-site measurements - Anomalous data - No maintenance and cleaning of the pyranometer - Recording period: December 2011 - November 2012

Table 4.2: Resume of the different analyzed datasets for solar radiation

Figure 4.10: Location of the different weather stations considered for the solar radiation assessment

4.1.2.2 Wind energy assessment

In order to evaluate the wind energy potential of an area, the knowledge of the wind speed is needed. The electrical output of a wind turbine depends on the wind speed by a cubic factor; thus, little variations of this parameter lead to huge differences in the electrical production.

The prevalent wind direction and the frequency of gusts are also important parameters affecting the design of a wind generator. In order to evaluate the frequency of gusts, a useful parameter is the Weibull shape parameter (k), that reflects the breadth of a distribution of wind speeds. An high k value implies a steady wind, whereas a low value an inconstant one.

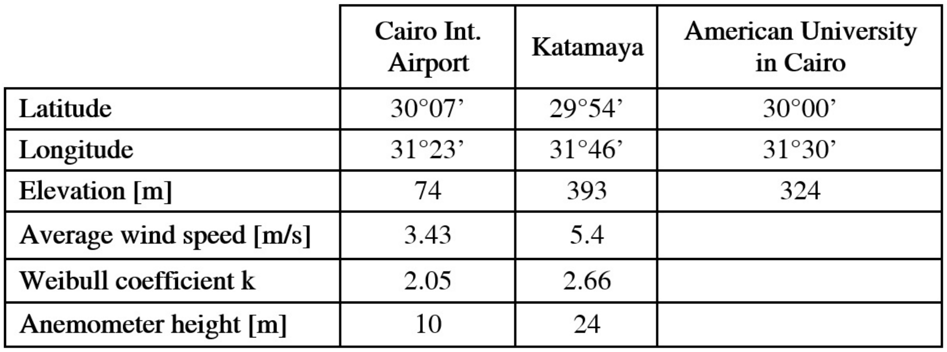
Wind is extremely site specific, since its parameters are strongly affected by obstacles and orography. Moreover, it is not constant during the day and it usually faces big seasonal variations. Thus, the online available global wind atlas (e.g the *IRENA's Global Atlas*) and the meteorological simulations are not accurate, despite all the efforts that have been made in the last years. Moreover, those atlas are usually based on the calculation of the wind speed at 50 m above the ground, which is much higher than the hub height of a small wind turbine ($\approx 10m$).

In order to identify the best site for the installation of a wind turbine, actual measurements throughout several years are needed. Usually, these data are not available, especially in rural areas and in developing countries like Egypt, and a measurement campaign is quite often not economically feasible for small wind turbines. Another option is to use data collected from nearby meteorological stations and extrapolate those for the specific context via forecasting models. AUC runs a meteorological station, but - as mentioned in paragraph 4.1.2.1 - its measurements are not reliable due to the lack of maintenance.

Therefore, the current study is based on a forecasting model validated through the comparison with data available from two nearby meteorological stations.

Review and evaluation of the available wind data The current study takes advantages of two actual wind datasets and it uses them as a benchmark for the forecasting model. Unfortunately, Egypt does not have a dense grid of weather stations and the institutions that own data regarding the wind resource are not eager to share them. Therefore, the reported data are the ones retrievable in the literature.

The first dataset is composed by a one-year measurement campaign at the Cairo airport, performed by Hamouda [168]. The second dataset was recorded in Katamaya, in the East Desert near New Cairo, within a wider anemometric campaign performed for the publication of the Egypt Wind Atlas [169]. This set comprehends one year of measurements. In table 4.3 the main information of the two weather stations and of the AUC campus are reported. It should be noted the quite different elevation of the three locations.



	Cairo Int. Airport	Katamaya	American University in Cairo
Latitude	30°07’	29°54’	30°00’
Longitude	31°23’	31°46’	31°30’
Elevation [m]	74	393	324
Average wind speed [m/s]	3.43	5.4	
Weibull coefficient k	2.05	2.66	
Anemometer height [m]	10	24	

Table 4.3: Wind weather stations characterization

Forecasting model Since the two datasets are related to locations far from the AUC, with different horography and altitude, and since the wind is site specific, a mathematical model is needed to calculate a synthetic reliable set of data. The current study takes advantage of the *Autodesk Climate Server* software, which is a worldwide database based on both mathematical models and actual measurements. The trial version of the software was used. Those data include dry bulb temperature, dew point temperature, relative humidity, wind speed and wind direction, direct normal radiation, global and diffuse horizontal radiation, and total sky cover, among others. *Autodesk Climate Server* is composed by 1.6 million virtual weather stations, created in order to establish a mesh of weather data based on meteorological simulations almost all over the earth surface. Those simulations are based on two forecast models: the Rapid Update Cycle (*RUC*) and the Mesoscale Model version 5 (*MM5*).

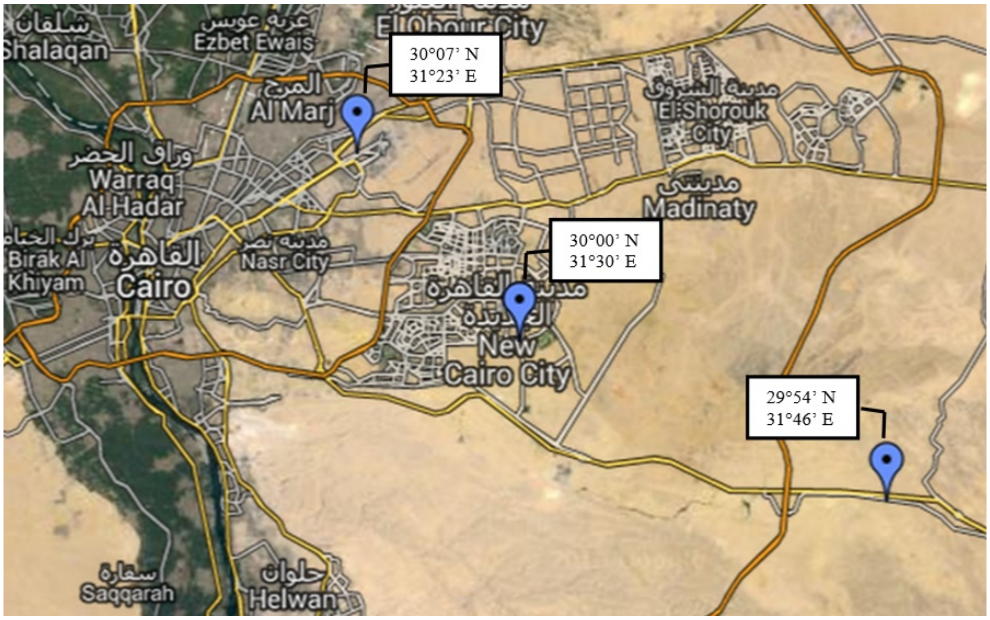


Figure 4.11: Location of AUC Campus and of the two weather stations considered for the wind energy assessment

The *RUC* model was developed by the *NOAA/NCEP*[3] of the United States of America. The *RUC* is an operational weather prediction system, which is based on a numerical forecast model, initialized by an assimilation and analysis system. The model is able to provide frequently updated short-range weather forecasts, taking as input recent observations to provide hourly updates of current conditions. The virtual stations of the *Autodesk Climate Server* are based on the current condition updates at the earth surface for each hour. The current conditions field is created using an optimal interpolation (*OI*) analysis, that assimilates observations and satellite data, and the previous one hour forecasts, that are calculated via mathematical models. *OI* interpolates meteorological observations spatially to generate an analysis field. Therefore, actual observations and simulations are together used to develop an hourly update of conditions very close to the real observations. The actual observations come from a large variety of sources, including surface reporting stations and buoys, commercial aircraft, wind profilers, SSM/I satellite data and many others. For further information see [170, 171].

The MM5 model is a limited-area, non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation, developed by the Penn State and NCAR [172]. Since it is a model suitable for limited area, the MM5 is used to integrate the RUC model, when a lack of data occurs.

The AUC campus is equally far from four different virtual weather stations, whose data

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[3] National Oceanic and Atmospheric administration / National Centers for Environmental Prediction

are reported in table 4.4. Moreover, the virtual station situated on Nasr City, an outskirt of Cairo, is reported as a benchmark of the usual wind speed in Cairo metropolitan area.

	Nasr City	South East	South West	North West	North East
Latitude [°]	30.06	29.95	29.96	30.06	30.08
Longitude [°]	31.3	31.45	31.58	31.43	31.56
Elevation [m]	76	335	239	157	224
Average wind speed [m/s]	3.208	4.65	4.45	3.97	4.256
K	2.35	2.39	2.53	2.36	2.26

Table 4.4: Wind virtual weather stations characterization

It is important to notice that the average wind speed grows with the altitude and that the model does not report huge differences in the Weibull shape parameter k. Figure 4.12 shows the clear relation between elevation and average wind speed, as simulated by the forecasting model.

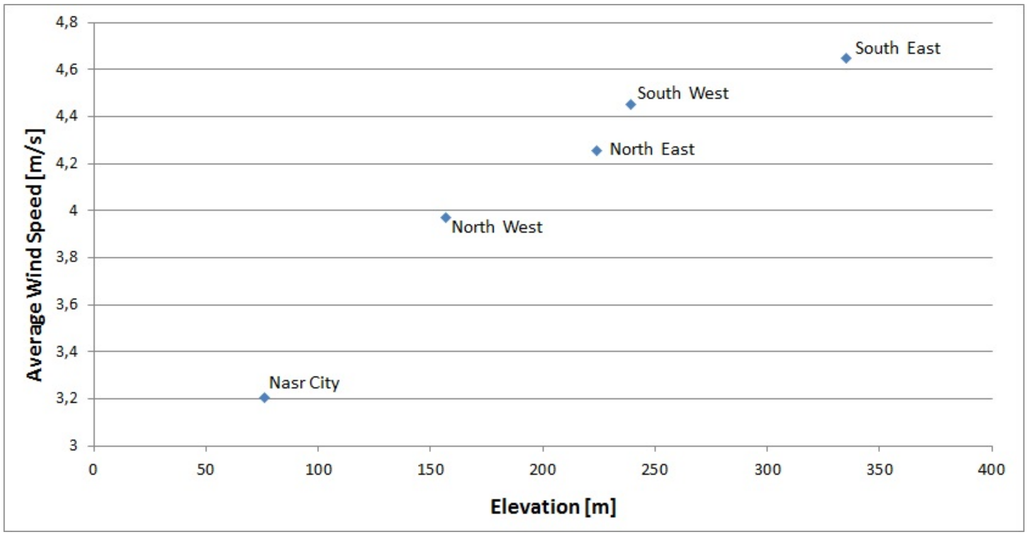


Figure 4.12: Elevation and average wind speed of the virtual weather stations

AUC wind weather data The four virtual stations report different values of wind speed; therefore, the choice of the correct station is crucial and must be based on the local context and on the two measured data series, which are related to the Cairo Airport and to Katamaya. There is a huge gap between the two average wind speed measurements, mainly because of the altitude difference. As a matter of facts, AUC lies on the highest point of New Cairo (324 m), on the boarder with the East desert. Therefore, the wind speed is expected to be more similar to the measurements of Katamaya than the ones taken at the Airport. The South East virtual weather station is the most appropriate for AUC context, since it is almost at the same elevation (335 m, figure 4.12). The average wind speed and the k parameter of this weather station result to be a middle way between the two sets of measured data.

This method is able to provide a roughly estimation of the wind energy potential of the AUC New Cairo campus. However, actual measurements are needed to validate this estimation. An anemometric campaign started in January 2015, aiming to provide an actual dataset for the AUC area; therefore it will be possible to validate this estimation at the end of the campaign.

Figures 4.13 and 4.14 report the monthly average wind speed and the wind direction for the South East weather station. The prevalent wind direction is north/north-east, thus the turbines must be placed freely exposed to the north direction.

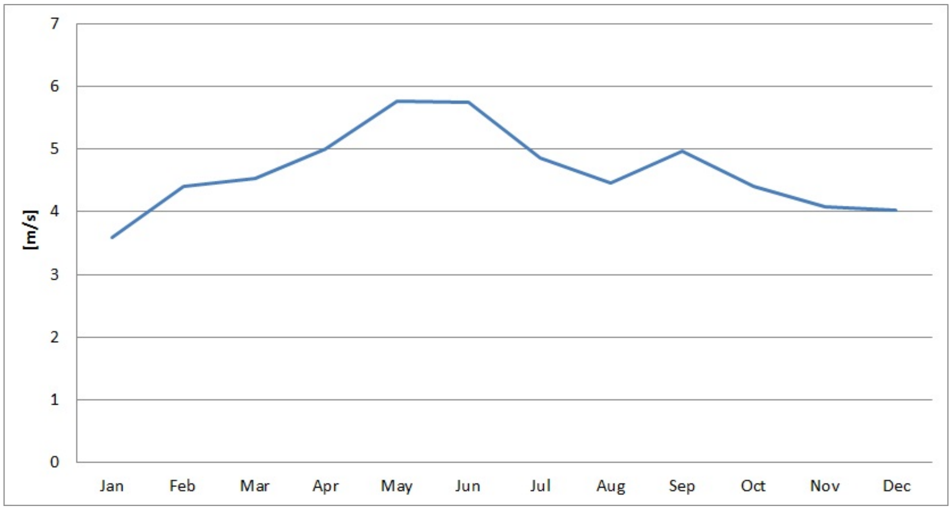


Figure 4.13: Monthly average wind speed of the South East weather station

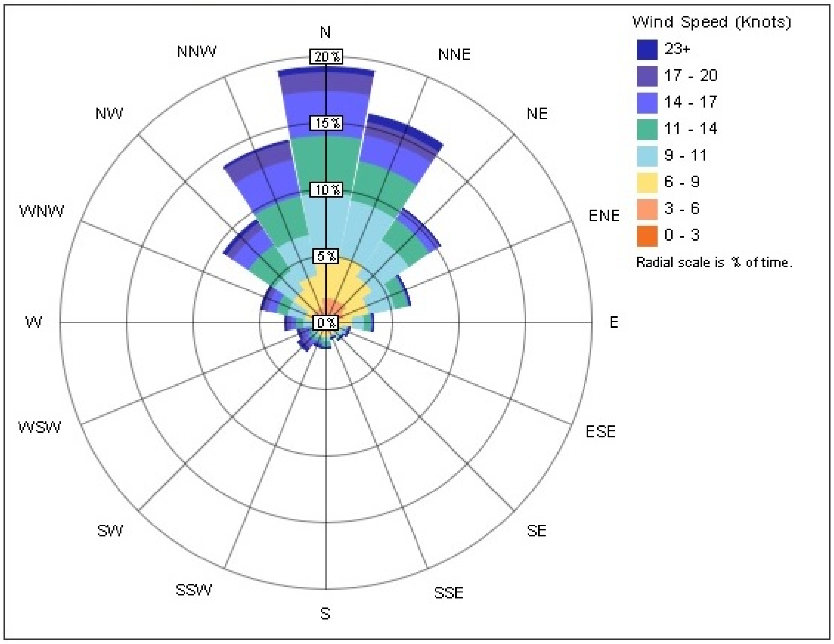


Figure 4.14: Annual wind rose of the South East weather station

Weibull distribution The average wind speed is not sufficient for evaluating the wind energy potential; thus, additional information regarding the wind speed distribution among the year are needed. The Weibull distribution gives these information; therefore, it was calculated for the synthesized wind data of the chosen virtual station. The Weibull distribution is a function expressed as:

$$f(v) = \frac{k}{c}(\frac{v}{c})^{k-1} exp[-(-v/c)^k]$$

Where $f(v)$ is the probability density function, i.e the probability that a wind speed at $v\,[m/s]$ blows through the project site; k is the shape parameter and c is the scale parameter. These two parameters define the function, thus identifying how many hours the wind blows with a certain intensity. Starting from the 8760 values given by the virtual weather station, the two parameters were calculated through the *maximum likelihood method* [173]. The Weibull distribution is presented in figure 4.15.

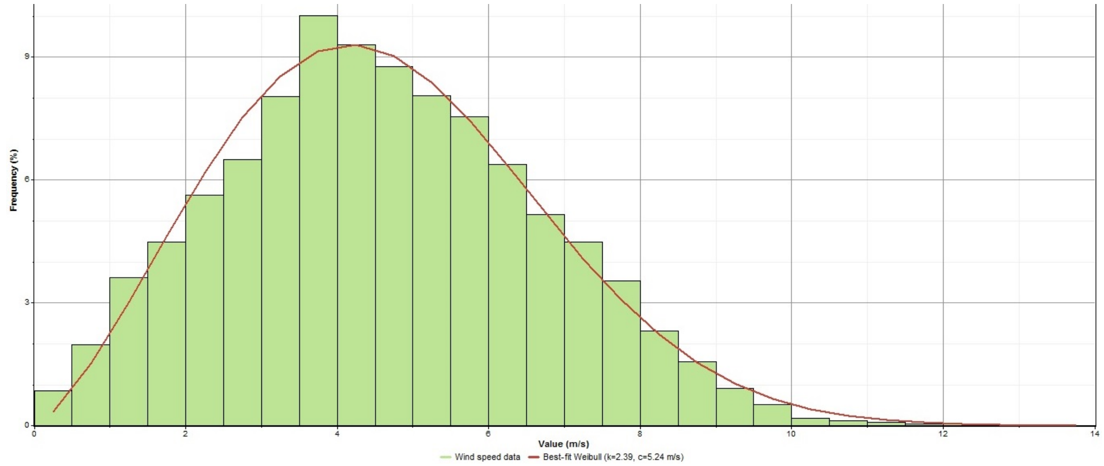


Figure 4.15: Weibull distribution of the South East weather station

4.1.2.3 Biomass energy assessment

The AUC campus produces organic waste in different forms. Since this study is focused on the possibility to employ organic waste as an energy source, the assessment has to take into account the current AUC policies on waste management. A list of the major organic matters produced is presented together with their currently employment within the university and their different treatments appropriate for energy production:

- Agriculture waste and yard trimmings. AUC is carrying on several projects on agriculture development, testing innovative solutions inside the campus itself. Moreover, a large number of palms, trees and gardens find place in the campus. Agriculture and vegetation produce a large amount of waste and yard trimmings. This organic matter can be used for the production of gas through anaerobic processes as gasification and digestion. However, agricultural waste and yard trimmings are currently collected by the Center for Desert Development and they are converted through an aerobic treatment to compost, used for crop's fertilization useful to reduce the need for irrigation.

- Wastewater and sewage sludge. Sewage sludge from wastewater treatment is frequently composted for fertilizer material production. However, it can also be used for energy production applications, mainly for the direct production of biogas through anaerobic digestion (AD). In 2012, AUC introduced treated wastewater for irrigation, aiming to reduce its water demand from Ismailiya Canal thus alleviating regional water scarcity and experiencing energy savings due to a lower energy demand for water pumping. Currently, treated wastewater is previously used water that enters the New Cairo sewer system and it is then pumped to an off-site treatment plant approximately 10 km east of New Cairo [174].

- Solid waste. As stated in AUC Carbon Footprint Report [174], a production of 614 MT of solid waste (SW) was estimated in 2012. Currently, the SW collected in the campus is entirely picked up by the trash community in Cairo, the Zabaleen. Unfortunately, a waste characterization study had never been carried out within the university; therefore, the actual composition of the waste stream is still unknown. The organic fraction of SW includes uncoated paper waste and food waste (FW) and it can be used for gas production through anaerobic processes.

Since the yard trimmings are already usefully used and the sewage sludge treatment implies several health and sanitation issues, unlikely AUC policies on these waste treatments will change in the short-term. Therefore, yard trimmings and sewage sludge cannot be considered currently available resources for energy production.

As for the SW, it has to be considered that the Zabaleen are a strong and tight-knit community in Cairo who supports itself by collecting trash door-to-door from the residents of Cairo and recycling it. It is estimated that they recycle more than the 75% of the waste. Discussing with the staff involved in the university waste disposal, it was pointed out that unlikely the agreement between the Zabaleen and AUC on all the recyclable waste will change, since for their community it represents the profitable portion of the collected waste. Therefore, the possibility of using paper waste for energy production was rejected expecting to continue the recycling disposal through the Zabaleen community in the near future.

Since the FW cannot be recycled by the Zabaleen and it currently remains unused, the leftovers of prepared food and the waste generated during food preparation are the most promising organic matters to be used for energy production. In particular, since the FW is typically wet biomass, the anaerobic digestion is the most appropriate way to treat it.

Food waste assessment

Conducting a waste characterization study is a critical first step in successful waste management planning, as an effective SW management requires a complete understanding of the composition of the waste stream [175, 176]. Similarly, detailed quantitative data on the amount, location and characteristics of the FW stream are required in order to identify the opportunities for energy production.

A variety of approaches have been adopted by researches and authors for assembling detailed data on SW, some of which include: reviewing waste management records, interviewing waste management staff and visual waste assessment. However, direct waste analysis offers the most effective process for an understanding of the actual composition of SW and FW [175]. Unfortunately, a direct assessment of the waste was prevented by the duration of the project, since a reliable estimation would have required at least one week of daily sorting and weighting during different seasons and different population density times. Moreover, as previously mentioned, no study or records were available on the composition of the SW produced in the campus: it was only known that in 2012 the university produced an estimated 614MT of SW [174].

Therefore, the current assessment is based on the analysis of scientific studies on the characterization of SW and FW produced in other university's campuses.

The share of FW over the total SW produced and the composition of the FW itself are now estimated extrapolating data from other institutions. Future on-field studies on the SW disposal and on the biomass assessment at AUC campus are requested in order to enhance the accuracy of the current estimation.

Amount of FW While several waste characterization studies have been carried out at the household or municipal level, only a small number have assessed the composition of SW within institutions of higher education. A large contribution on the topic comes from Canadian institutions: waste audits at four different universities revealed that food waste represented between 17 and 29% of the total campus waste stream [175, 177]. However, a waste characterization study performed in one Campus of the Autonomous University of Baja California (AUBC), in Mexico, found that organic waste represented 35.5% of the total waste stream. This sensible variation can be explained by a different definition of *organic waste*: the AUBC study counted as *organic waste* the yard trimmings and the harvest waste in addition to the FW.

Furthermore, Mbuligwe [178] reported considerably higher share of organic waste in three Tanzanian institutions (more than 50%), to the detriment of plastics, glass and metals. However, these results show that the trash composition is deeply affected by the socioeconomic status of the people responsible of the waste: in developing countries the weight share of organic waste can be considerably higher than in developed countries.

As for the AUC, since it experiences an international and wealthy environment, a waste stream composition comparable to the developed countries' institutions is expected. Therefore, the food waste can be likely expected to represent between 17 and 29% of the total campus waste stream. Set a yearly production of 614 MT of solid waste (SW), the food waste generation is expected to lie between 100 and 180 MT per year.

Composition of FW The FW biomass is mainly characterized by the total solid content (TS) and by the volatile solid content (VS), which is the share TS that can be converted into biogas. The TS strongly depends on the FW composition: the different share of vegetables, meat, eggs and other type of food leads to various biogas potential and those shares will vary according to the local eating habits. According to several experimental studies, a standard food waste composition is composed by organic matter that has a TS between 18%-30%, which means an high water content [179, 180, 181]. The ratio of VS to TS ($\% VS/TS$) is greater than 80%, thus the amount of TS convertible in biogas is very high. According to Grimberg et al. [182], the average production of biogas from FW can be expected to lie between 0.1 and 0.15 m^3/kg of wet fed biomass. This value is confirmed by the Integrated Waste Management board of California [183], that performed a market analysis over already running organic waste digesters, and by the lab-scale plant reported by Wei Qiao et al. [184].

Thus, the biogas yearly produced from AUC food waste can be expected to lie between 10 and 27 $*10^9 m^3$. However, it should be noted that the reported number is the theoretical maximum production: as a matter of facts, a standard digester takes a long time to convert the FW in biogas, which is called *retention time*. Hence, several digesters would be needed in order to convert all the FW collected at the AUC campus into biogas, which is not a practicable solution.

4.1.3 Development and evaluation of different RES layouts

4.1.3.1 Simulation software for renewable energy systems: *HOMER Energy*

There are several different RES layouts that can be implemented to provide the amount of energy required by the desalination laboratory. It is difficult to understand which is the best option among hundreds of alternatives, considering the constraints given by the local environment. In order to evaluate the performance of each layout and compare them on techno-economic parameters, *HOMER Energy* software was used.

HOMER Energy is a software developed by National Renewable Energy Lab of the US Department of Energy, and it is focused on the simulation of micro and mini RES, both on-grid and off-grid.
HOMER Energy is able to perform three types of simulation:

Feasibility The user sets a number of different plant layouts to be simulated and the software checks if each configuration is able to cover the electrical load or not by making energy balances hour by hour for 365 days

Economical The levelized cost of energy (LCOE) for each feasible solution is calculate, so that the solutions are sorted from the most economical to the most expensive.

Sensitivity The user is able to change some structural parameters (such as the solar radiation data) and ask the software for a sensitive analysis. *HOMER Energy* will re-simulate every configuration with the new parameters, thus allowing the user to study the behavior of the system in different situations.

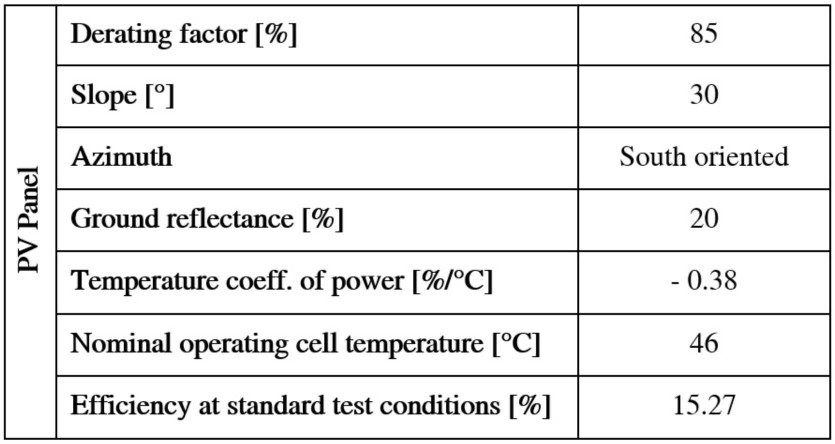
HOMER Energy needs a large number of input data to perform a simulation, which are divided in:

- Natural resources data
- Electrical load data
- Constraints data
- Equipment data

Natural resources and electrical load data were collected through the resources assessment and the load evaluation. The constraints data, which comprehend among many others the minimum capacity shortage of the system and the minimum load reserve, were changed according to the goal of the simulation.

The techno-economical features of the equipment were based on devices actually available on the Egyptian market.

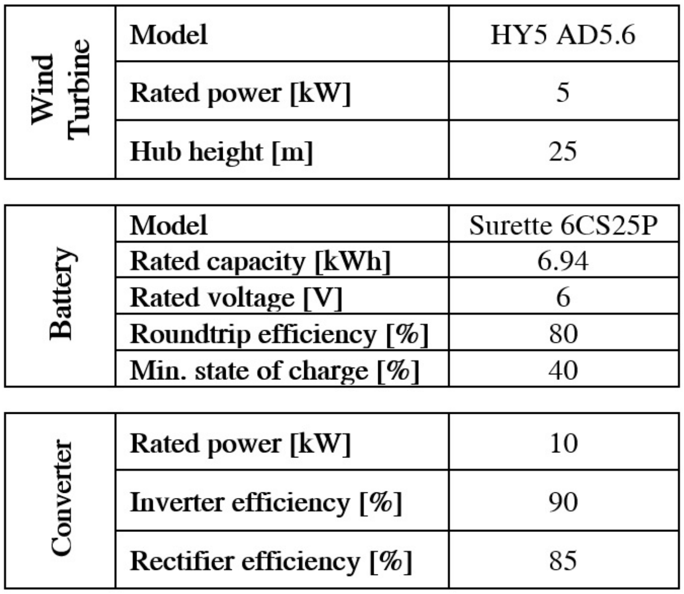
Table 4.5 reports the technical features of the implemented PV panel. It is important to underline that the derating factor considers all the detrimental effects that the environment might have on the PV panel, in particular shadowing and dust soiling effects.



PV Panel	**Derating factor [%]**	85
	Slope [°]	30
	Azimuth	South oriented
	Ground reflectance [%]	20
	Temperature coeff. of power [%/°C]	- 0.38
	Nominal operating cell temperature [°C]	46
	Efficiency at standard test conditions [%]	15.27

Table 4.5: Technical features of the implemented PV panel

Table 4.6 shows the technical features of the other devices composing the system, namely wind turbine, battery and converter.



Wind Turbine	**Model**	HY5 AD5.6
	Rated power [kW]	5
	Hub height [m]	25
Battery	**Model**	Surette 6CS25P
	Rated capacity [kWh]	6.94
	Rated voltage [V]	6
	Roundtrip efficiency [%]	80
	Min. state of charge [%]	40
Converter	**Rated power [kW]**	10
	Inverter efficiency [%]	90
	Rectifier efficiency [%]	85

Table 4.6: Technical features of the implemented wind turbine, battery and converter

Finally, the capital cost of the each device is reported in table 4.7. It should be noted that other costs such as operation and maintenance and replacement costs are not estimated, since the calculation of the LCOE was not requested, as it will be better explained in the following section.

	PV panel	Wind turbine	Battery	Inverter
Capital cost [$]	1,833 $/kW	8,906 $/unit	1,170 $/unit	700 $/kW

Table 4.7: Capital cost of the implemented equipment

4.1.3.2 Simulations results

HOMER Energy is able to simulate several kinds of RES, providing an estimation about the behavior of the systems during a standard year. The aim of the simulations is to compare different layouts, in order to understand the effects of the different devices of the system[4] on the whole RES and to identify which is the best configuration for the local context, without performing a detailed design.

The most important information gained from the simulations are the system installed power and the capital cost. The goal of the laboratory is to run tests on desalination technologies coupled with RES, regardless the LCOE of the produced energy, which means that the cost of the freshwater is not an issue. The capital cost is instead more important, since the budget of the project was limited. As a pre-feasibility study, the equipment technical and economical data of standard devices retrievable on the Egyptian market were employed.

It was decided to consider technologies appropriate for micro-grid applications, such as small wind generators, PV systems and biogas engines. The CSD decided to do not employ a diesel engine, in order to avoid its environmental impact. Since there are several different combinations of solar, wind and biogas engine, the following paragraphs report only some examples of the performed simulations, which are useful to achieve a deeper understanding of the behavior of the system. Table 4.8 reports the developed simulation matrix.

		RES system			
		PV based	**Wind based**	**Hybrid (PV+Wind based)**	**Biomass based**
Scenario	**On-grid**	PV_Ongrid	Wind_Ongrid	Hybrid__Ongrid	-
	Off-grid	PV_Offgrid	Wind__Offgrid	Hybrid__Offgrid	Bio_Offgrid

Table 4.8: Matrix of the performed simulations

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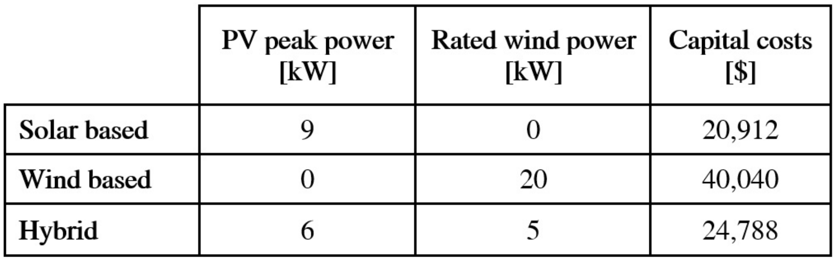
[4] Power production device, storage, inverter etc

First scenario: on-grid The first scenario takes into account an on-grid system, powered by solar and/or wind energy. The produced power is fed firstly to the desalination electrical load, secondly to the grid. The grid is employed as a backup system: it is able to receive energy from the RES when the production exceeds the demand and to give it back to the laboratory when needed. It is assumed that there is no shadowing on the PV panels and the wind is not disturbed by surrounding buildings.

Each reported layout is able to produce the amount of expected energy needed by the load in a standard year, using the grid as a storage, so that the amount of energy fed to the grid is equal to the one taken from the grid itself.



	PV peak power [kW]	Rated wind power [kW]	Capital costs [$]
Solar based	9	0	20,912
Wind based	0	20	40,040
Hybrid	6	5	24,788

Table 4.9: First scenario: the results of the on-grid simulations

Table 4.9 shows the results of the simulations. It is clear that the wind system is less efficient than the solar one: the rated power required to supply the same load is higher for the wind based system. Therefore, the capital cost, which depends on the rated power, is higher for the wind powered system than the solar one. The hybrid system is able to feed the load using a combination of solar and wind energy that is a more-expensive solution than a solar based system, due to the presence of the wind turbines. Moreover, the hybrid system requires a more-expensive solar/wind inverter, since it requires a more difficult and sophisticated control logic.

A solar based system needs a large amount of area for the installation, which is not always available. An hybrid system might reduce the area required by the PV system, since a wind turbine might be integrated more easily with the surrounding buildings. This area reduction is strongly affected by the local context; thus, it cannot be estimated in a pre-feasibility study.

Second scenario: off-grid The second scenario is an off-grid system, able to feed the load without using the grid, employing the equipment of the first scenario, with an additional battery storage able to provide the needed electrical backup. Each configuration reported in table 4.10 is able to feed at least the 95% of the annual load.

An off-grid system requires a larger amount of installed power, since the system has to cover the load even if the natural resources are not available. It also requires a huge battery storage, which leads to higher capital cost and to more complex and costly maintenance and management of the system. In addition, the system employing wind turbines needs a battery

	PV peak power [kW]	Rated wind power [kW]	Batteries capacity [kWh]	Capital costs [$]
Solar based	17	0	60.8	38,904
Wind based	0	30	380	107,000
Hybrid	14	2	105	68.024

Table 4.10: Second scenario: the results of the off-grid simulations

system larger than the PV one: the wind power output is less predictable than the one coming from a PV system, and it might change a lot during the day; thus, it has to be stabilized by a larger battery storage. The reported hybrid configuration is a middle way between the solar and the wind powered system.

Another alternative simulated only for the off-grid scenario considers the employing of a gas engine, powered by biogas produced by a food waste (FW) digester. The biogas that can be obtained from the AUC's FW is able to cover all the electrical load without any backup system such as grid or battery storage, but a huge digester would be needed in order to convert such a large amount of FW to biogas. A huge system is not feasible for the AUC context, since the local policy on new structures does not allow the construction of new large buildings: only the construction of a small-scale biogas system might be approved.

In order to understand if a small-scale system is able to cover the laboratory electrical load, the current study takes advantage of the work of S.J. Grimberg et al. [182], which describes a digester unit used for converting the FW of the Clarkson University cafeteria into biogas. The hypothesis of using the same AD process is made, since Grimberg takes into account university's FW and the process can be easily implemented at the AUC.

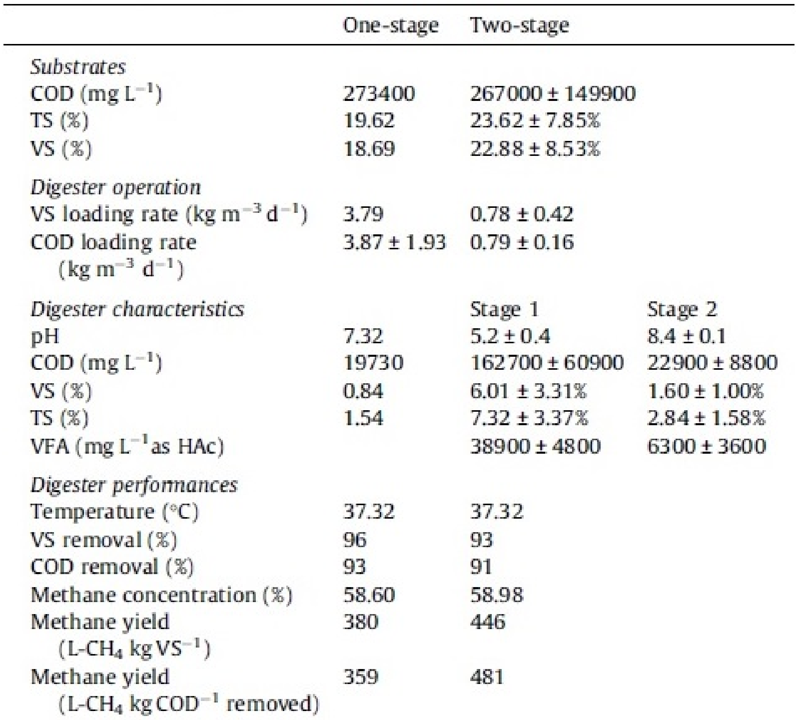
The system consists of a grinder, a ribbon blender and three neoprene-insulated $5m^3$reactors that can operate in series or in parallel. The FW is shredded and diluted, in order to enhance the digestion and to be easily pumped. An overview of the main parameters of the Clarkson University digester operation is shown in figure 4.16.

The specific methane yield results to be 380 $\frac{L-CH_4}{KgVS}$ for a single stage system, which is the simplest one. The Clarkson Univeristy digester has a volatile solid fraction (VS) loading rate of 3.79 $\frac{kg}{m^3day}$ and a total digester volume of 15 m^3. Thus, the daily VS input results:

$$3.79\,\frac{kgVS}{m^3day} * 15\,m^3 = 56.85\,kgVS/day$$

Therefore, the daily methane production is:

$$56.85\,kgVS/day * 380\,\frac{L-CH_4}{kgVS}/1000 = 21.60\,m^3$$



	One-stage	Two-stage	
Substrates			
COD (mg L^{-1})	273400	267000 ± 149900	
TS (%)	19.62	23.62 ± 7.85%	
VS (%)	18.69	22.88 ± 8.53%	
Digester operation			
VS loading rate (kg m^{-3} d^{-1})	3.79	0.78 ± 0.42	
COD loading rate (kg m^{-3} d^{-1})	3.87 ± 1.93	0.79 ± 0.16	
Digester characteristics		Stage 1	Stage 2
pH	7.32	5.2 ± 0.4	8.4 ± 0.1
COD (mg L^{-1})	19730	162700 ± 60900	22900 ± 8800
VS (%)	0.84	6.01 ± 3.31%	1.60 ± 1.00%
TS (%)	1.54	7.32 ± 3.37%	2.84 ± 1.58%
VFA (mg L^{-1}as HAc)		38900 ± 4800	6300 ± 3600
Digester performances			
Temperature (°C)	37.32	37.32	
VS removal (%)	96	93	
COD removal (%)	93	91	
Methane concentration (%)	58.60	58.98	
Methane yield (L-CH_4 kg VS^{-1})	380	446	
Methane yield (L-CH_4 kg COD^{-1} removed)	359	481	

Figure 4.16: Parameters summary of the Clarkson University digester [182]

The amount of FW produced at the AUC is much higher than the one requested to feed the small three-batch digester. Therefore, it is possible to assume that this methane production can be achieved at the AUC.

The produced methane has to be converted in electricity via gas engine. Assuming that the rated power of the engine is 10 kW and the average efficiency is 20%, the biogas system is able to supply the load. However, this is a roughly estimation that does not consider the real operation of the engine and the actual availability of the biomass during the year.

The costs of a biogas system are strongly affected by the supply chain of the biomass: although the capital cost can be predicted, the costs related to the biomass collection and treatment should be not underestimated. Therefore, it is necessary to calculate the costs of the biomass supply chain, which might be calculated only after a detailed design.

Conclusion Table 4.11 shows the strengths and weaknesses of each configuration. It is clear that a PV system is more efficient than a wind system in this context. The biogas configuration has the potential to overcome the PV system; however, the costs and the complexity of establishing an appropriate supply chain it should be not underestimated, especially in the AUC context. Therefore, the CSD selected a PV based system for powering the desalination

	Strengths	**Weaknesses**
PV system	- Less installed power required - Less capital costs - Less batteries required for the off-grid scenario	- A large area without shadowing is required
Wind turbines	- It might be integrated with the surrounding buildings	- High installed power required - High capital costs - Many batteries are required for the off-grid scenario
Solar/Wind system	- The wind turbines can integrate the PV production, thus reducing the area required for the solar system and the battery storage	- More complex and expensive than a system based only on PV
Biogas system	- It does not require a large area - It might be installed everywhere, without particular constraints - It reduces the environmental impact of the campus, thanks to the FW recycling	- It requires a complex supply chain, that has to be managed constantly throughout the year - The power production relies on the availability of the FW

Table 4.11: Simulation scenarios resume: strengths and weaknesses

laboratory, thanks to its simplicity, reliability and costs.

4.2 PV system design

Once the most appropriate RES was selected, the detailed design of the PV system was carried out on-field, in order to collect all the data required and to collaborate with the people involved in the desalination laboratory. Therefore, many non-technical issues had to be faced, such as unreliable data and lack of coordination and know-how. The present section aims to show the technical guidelines that were followed during the on-field design, whereas Appendix 1 will report the actual sequence of activities and the problems faced.

4.2.1 Activities flow chart

In order to select and design the most proper PV system layout and the best supplier able to provide the system, the procedure showed by the flow chart in figure 4.17 was followed.

The first two tasks were the load evaluation and the energy assessment activities, which have been previously described, and that could be carried out simultaneously; the output of these activities were the electrical load profile and the solar radiation intensity over a standard year. The energy simulations, performed through *HOMER Energy*, were based on these two

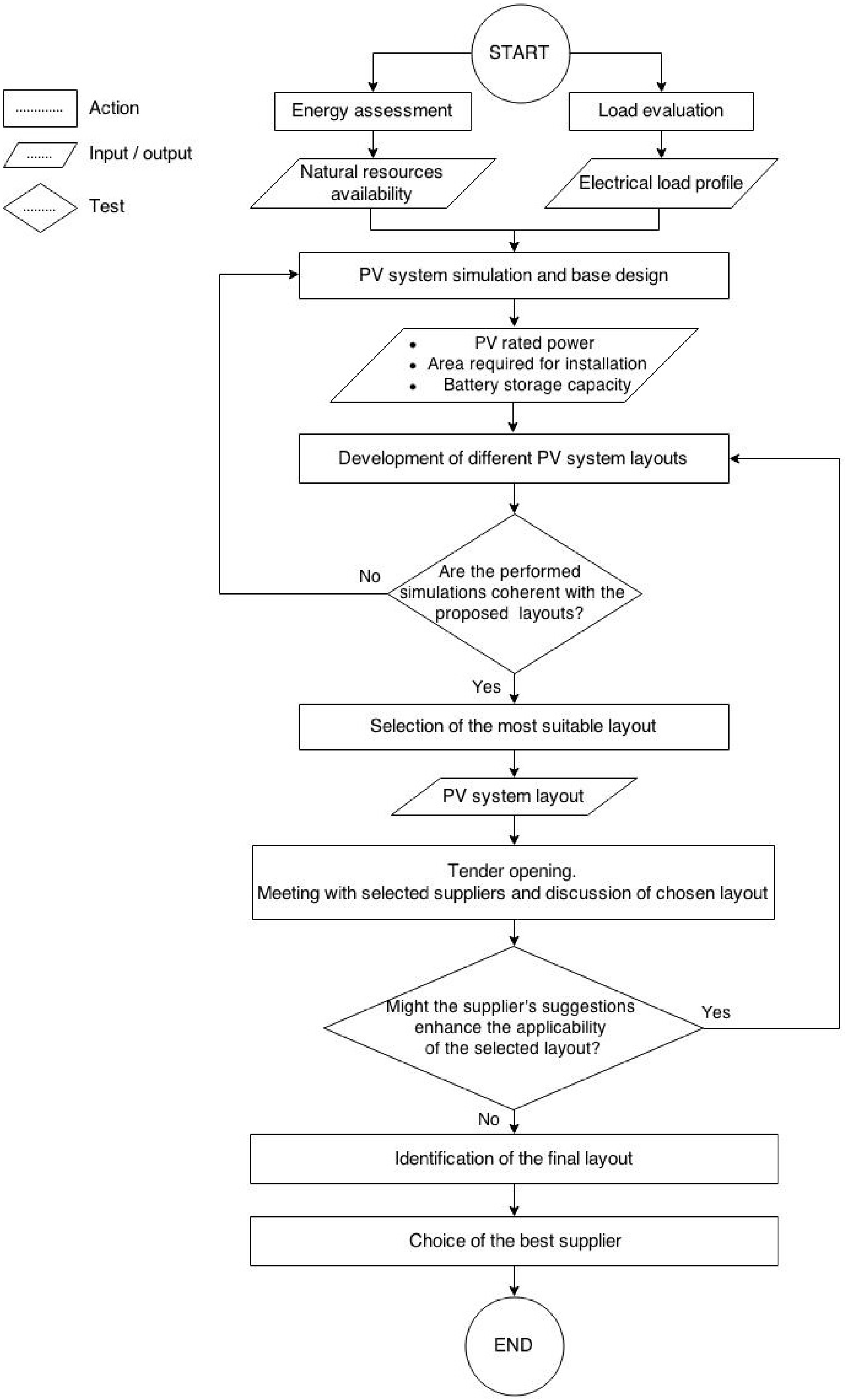


Figure 4.17: PV system selection and design process flow chart

outputs and they provided the needed PV rated power, the area required for the installation of the panels and the battery storage capacity.

Thanks to these information, it was possible to design several PV plants layouts, which comprehend the placement of the panels and the design of the structure able to support them. These layouts may affect the simulation's parameters[5]; hence, it was mandatory to simulate again several systems, until a set of possible layouts together with the energy performances was identified; among them, it was then possible to choose the most appropriate layout. Once the layout was selected, the tender among the local PV system's suppliers was opened.

Since the local suppliers have an on-field experience, they gave suggestions and information that changed the applicability of the layouts. Therefore, it was necessary to design again the selected layout, or to develop other configurations, previously not considered. At the end of this process, the final layout was identified.

In the final step of the process, the quotations based on the selected layout sent by the suppliers were evaluated, and the best one was chosen. The following paragraphs show in detail the procedure by which the layouts were developed.

4.2.2 Selection of the best PV system layout

As it was already stated in subsection 4.1.3.2, a main issue related with the solar panels is the area required for the installation. Since the laboratory is located inside the AUC campus, the area available for the installation was limited. Hence, it was mandatory to identify exactly the area required by the PV panels feeding the laboratory's load, and to develop layouts able to maximize the area exploitation, while minimizing the shadowing between panels and from other buildings. The energy simulations were carried out through *Homer Energy*, whereas trail versions of *SketchUp 2014* and of *DesignBuilder* were employed to calculate the energy losses due to the shadowing effect for each layout.

The energy fluxes of the PV system are reported in figure 4.18.

Two parameters useful to evaluate the energy performances of each layout need to be defined:

- The *indirect share*, which is the percentage of the ratio between the electricity outgoing from the inverter and the total electrical energy required by the desalination laboratory:

$$Share_{EEindirect} = \frac{I_g + I_d}{I_g + G} * 100$$

An indirect share equal to 100% means that the energy given to the grid in a standard year is equal to the one withdrawn. Hence, the PV system is able to provide 100% of the required energy using the grid as a backup system.

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[5] for instance, the shadowing between the panels cast by the surrounding buildings might change, on the basis of the different layouts, thus changing the PV energy output.

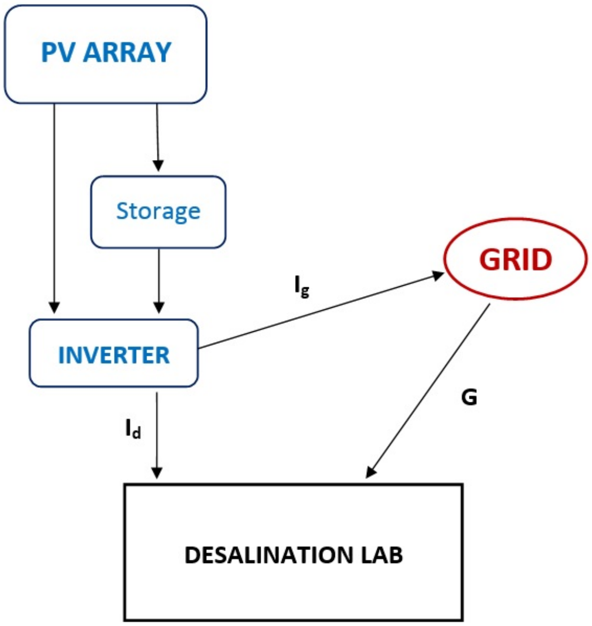

Figure 4.18: Schematic electricity flows of the PV system

- The *direct share*, which is the percentage of the ratio between the electrical energy directly fed from the PV system to the desalination laboratory and the total electricity required by the laboratory:

$$Share_{EEdirect} = \frac{I_g}{I_g + G} * 100$$

A direct share equal 100% implies that all the energy consumed by the desalination laboratory is provided directly by the PV system, without using the grid.

The energy performances of each layout were evaluated for two different scenarios:

On-grid The PV system is connected to the grid and the desalination laboratory is fed only by the grid: a direct flux from the inverter to the laboratory is excluded ($I_d = 0$). No battery storage is considered and the needed inverter is an on-grid one, thus being very cheap. The aim of this scenario is to achieve an indirect share equal to 100%, so that the research facility would be able to rely only on renewable energy provided the grid working as a energy storage. The on-grid scenario is the simplest and the cheapest, but it is not flexible. As a matter of facts, it does not allow researches and tests on both a remote off-grid area scenario and on the coupling between PV panels and membrane technologies, because there is not a direct connection between the PV system and the desalination laboratory. The direct share is zero.

Hybrid The PV system is connected both to the grid and to the desalination laboratory. A battery storage able to feed the full load for at least two hours, in case of a shutdown of the PV system, is needed. The grid is employed as an emergency backup, and it withdraws the excess electricity from the PV system. The aim of this scenario is to achieve the 100% of indirect share, but also to be able to simulate real off-grid systems. Therefore, inverters able to directly feed the load are needed. The direct share is obviously greater than the on-grid's one. This scenario is more expensive due to the increased cost of both the battery storage and the inverter.

The second scenario was agreed to be the most appropriate for a research facility. The two-hours battery storage capacity was determined as a trade off between the system flexibility and the cost: as a matter of facts, an higher storage capacity implies an higher direct share, and hence longer off-grid tests operations.

The PV system layouts were developed in collaboration with the AUC's Architecture Department. The A, B and C layouts sketched by the Architecture Department are reported in figures 4.19, 4.20 and 4.21.

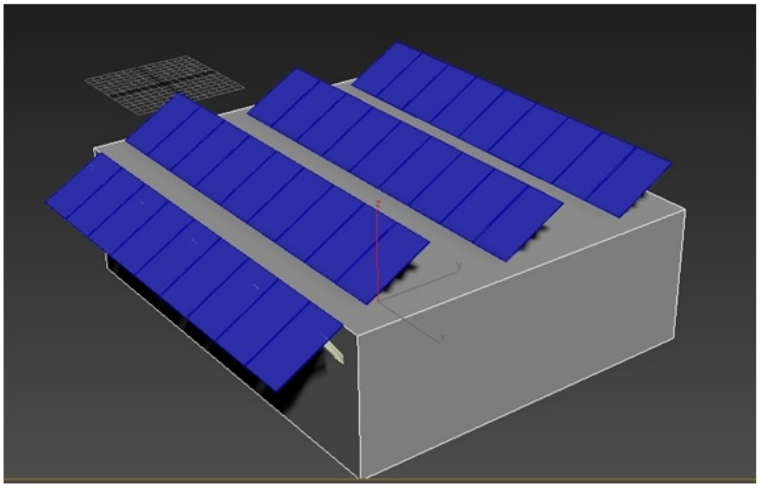

Figure 4.19: Layout A: only-roof layout

As it was shown in the activities flow chart (figure 4.17), it is important to remember that the process that led from the energy simulations to the layout design was iterative.

At the end of this process, the layout C was selected, since:

- It is able to shade the chemical storage tanks placed on the south face of the desalination building from the solar radiation. De facto, those chemicals require to be shielded from the solar radiation, due to safety reason.

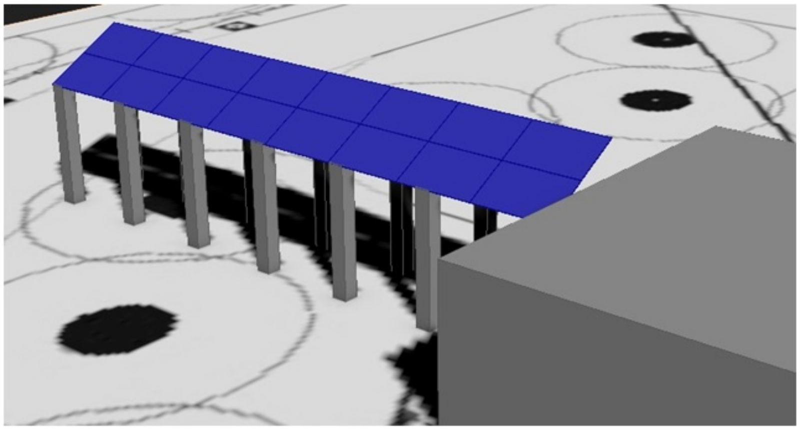

Figure 4.20: Layout B: corridor layout

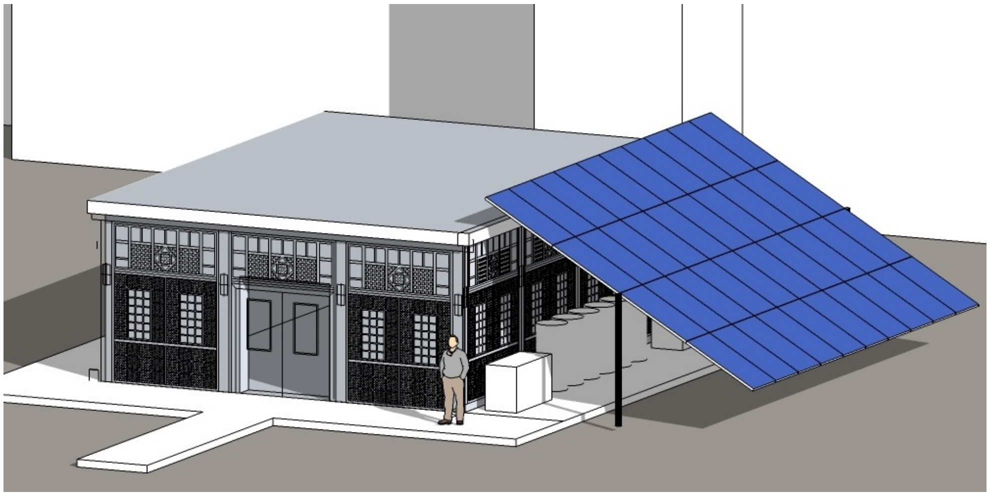

Figure 4.21: Layout C: elevation layout

- It minimizes the energy losses due to the shadowing caused by the surroundings buildings.
- The panels displacement reduces to zero the energy losses related to the shadowing between panels.
- Layout C does not employed the roof of the laboratory, which it was not able to support the installation of the PV system

The structure shown in figure 4.21 is able to support the installation of 40 panels, for a total rated power of 10 kW.

The performances of layout C were calculated through HOMER energy, using the input data previously reported (tables 4.54.64.7) and the shadowing coefficient calculated for this layout (see table 4.12).

	Number of modules	**PV peak power [kW]**	**Batteries capacity [kWh]**	**Direct share**	**Indirect share**
On-grid	40	10	-	0	1
Hybrid	40	10	15.84	0.74	0.97

Table 4.12: On-grid and hybrid scenarios performances of the selected layout

It is important to notice that the hybrid scenario shows a lesser value of the indirect share, compared to the On-grid one, due to the energy losses introduced by the battery storage. As a matter of facts, the battery storage is characterized by an efficiency lower than one, thus implying that the energy discharged is lesser than the energy that was fed to the battery.

4.2.3 Selection of the best offer of the suppliers

A list of eligible suppliers was drawn up, through an analysis of the Egyptian PV system market. All the eligible suppliers were asked for a quotation of the selected layout for the two scenarios, hybrid and on-grid. An electrical engineer from AUC was suggested to be consulted in order to properly face the problems related to the electrical connection of the system.

Then, two types of quotation, hybrid and on-grid scenario, were evaluated. As for the hybrid scenario, the suppliers presented different solutions for directly feeding the desalination equipment, whereas the on-grid quotations were similar and standard and they presented only cost differences. Eventually, the hybrid solution presented in figure 4.22 was indicated as the most promising and it was considered worthy of being examined in depth. However, the decision is still under discussion.

The system is composed by:

- 10 kWp polycrystalline photovoltaic modules consisting of two strings in parallel, composed by 20 modules connected in series;
- 1 on-grid inverter, with rated power 12.0 kW;
- 3 Variable Frequency Drive (VFD) inverters, coupled with the pumps;
- 1 Uninterruptible Power Supply (UPS), with rated power of 20 kVA and a backup system 20 kWh

The system is able to work in the on-grid mode, as well as in the off-grid mode, thus providing the flexibility required by a research facility.

In the on-grid mode, the photovoltaic modules are connected both to the load and to the utility grid. The inverter is set to feed firstly the load through the ripple control receiver (RCR), and secondly the utility grid of the university.

In the off-grid mode, the UPS feeds the load and the on-grid inverter is switched off. The VFDs, each coupled with a different pump, make the starting current of the pumps equal to the rated one.

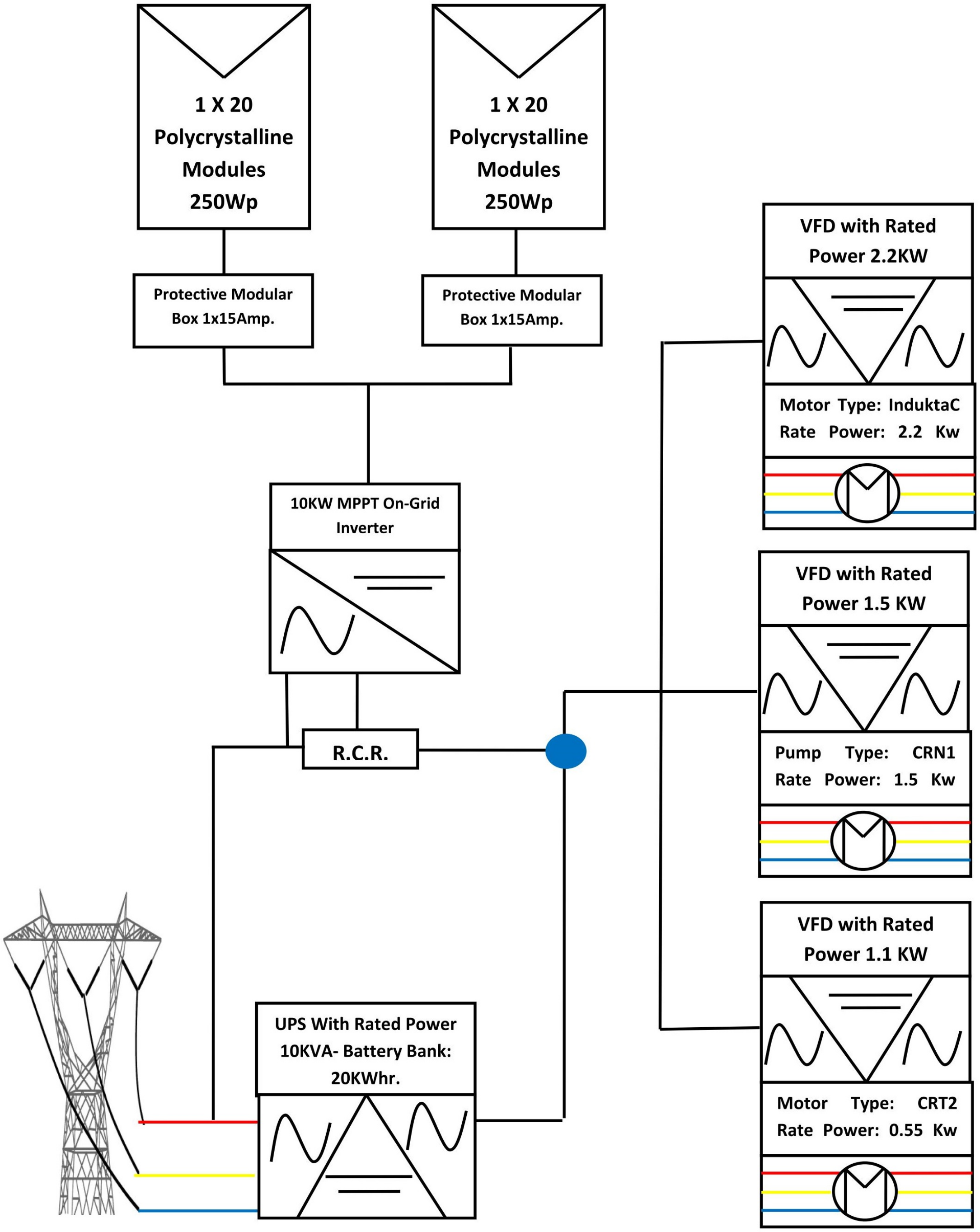

Figure 4.22: Schematic layout of the most promising offer

Chapter 5

Conclusions

Rural areas are not able to face the water scarcity, because of the lack of access to sources of modern energy. Therefore, addressing the water scarcity in rural areas means, even more than in urbanized water-scarce areas, addressing the related energy requirements. The present thesis aims to address the water and energy nexus focusing on the technical solutions appropriate for off-grid rural desalination. The study underlines these solutions have to be selected and designed considering the economic, environmental and social dimensions of sustainability.

Three main steps were followed:

Critical review Five desalination technologies were identified as appropriate for off-grid rural applications. The main techno-economical features of each technology, with a particular attention to the energy consumption, were then analyzed. Moreover, the distinct features of each technology in terms of advantages and disadvantages and a comprehensive performance and technical analysis of the desalination systems were provided. Eventually, a general comparison between the selected desalination technologies was given.

From the critical review, it emerges that, among the several possible combinations of desalination and energy technologies, some seem to be more promising in terms of technological and economic feasibility than others. However, there is no *best* method of desalination since the applicability of the desalination solutions strongly depends on local circumstances. Moreover, it emerges that there is a growing need for on-going research and demonstration projects to gain experience, knowledge and trust in these new simple, low maintenance, small-scale sustainable desalination technologies. In particular, in order to tackle in a fully sustainable way the water and energy scarcity, comprehensive research and development programs involving all the stakeholders of a rural area desalination project are required.

Decision method Because of the advantages and disadvantages associated with each desalination system, the selection of the most appropriate technology for a specific rural area is a complicated task. A multi-attribute decision method based on the Analytic Hierarchy

Process was developed, in order to assist non-technical decision-makers in the selection of the most appropriate desalination technology for a rural context. An appropriate hierarchy and a set of economical, environmental and social indicators were defined as a result of the critical review previously described. The formulation of the decision method pointed out that the selection of a desalination technology must be based on criteria evaluating the three pillars of the sustainability. The decision method was tested on a desalination plant already successfully established in a rural village, designed by the Istituto Tecnològico de Canaria (ITC). It resulted that the model identified as the most appropriate the same desalination technology chosen by the technical experts of the ITC, hence proving the reliability of the model. From the application of the model, it came out the essential role of the local stakeholders in the decision process. It is important to underline that, to be able to properly apply the decision method, a deep understanding of the local context is needed.

RES assessment and design for rural desalination Once the technology is identified, it is necessary to proceed with the detailed design of the desalination system. The current study presented the pre-feasibility study and the actual design of a renewable energy system intended to power a desalination research facility, established at the American University in Cairo. The pre-feasibility study included the detailed analysis of the energy requirements of the laboratory together with an accurate assessment of the renewable energy potential of the AUC campus. As it emerged from this study, the challenges related to the data reliability and availability must be considered in developing countries. As an output of the pre-feasibility study, a photovoltaic system resulted to be the most appropriate solution for powering the desalination laboratory. The detailed design of the PV system was eventually presented. The challenges of working in a developing country emerged from the design, thus pointing out the importance to adapt the mindset of the authors and to understand the local culture.

Some further developments could be the following:

- A market analysis can integrate the critical review of the scientific literature providing useful information on the commercial availability and actual figures of the analyzed technologies.
- Application of the model to other real case studies in order to enhance the validation of the set of criteria and indicators. In particular, the challenges related to the utilization of the model by non-technical decision-makers must be identified.
- The assessment of the renewable sources available at the American University in Cairo might be validate through on-field measurement campaigns.

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