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WEF APPROACH IN THE INTEGRATED WATER-ENERGY DESIGN FOR IRRIGATION SYSTEMS

CASE STUDY IN ERITREA

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ABSTRACT

The energy and water dimensions are strictly linked in the agricultural context. Crops growth requires water, which needs energy to be pumped and distributed in fields. Agriculture could be strongly enhanced in terms of quality and quantity of food products through a conscious use of water and a sustainable energy generation. While agriculture has significantly changed in recent years, these changes have not been going forward the same direction worldwide. Global phenomena of climate change, land grabbing and uncontrolled urbanisation are jeopardising the sustainable exploitation of natural resources, firstly in developing countries. The major inefficiencies in energy and agricultural water use are observed in the same countries where energy access and food security are not guaranteed.

In this work, an integrated water energy design for irrigation systems is presented, though the analysis of a case study in a rural farm in Eritrea. The purpose is to prove the direct linkages among water withdrawals, irrigation method applied in field and energy request. The current situation of energy and water consumption of the actual irrigation system, observed during the author's field experience, is compared with two design approaches about an improved energy system: a demand driven approach and an integrated design of the energy and water system. The first one faces the sizing process of the energy system without considering the calculation of the water needs of local agricultural products. In the second one, the energy load curve needed to pump and distribute water is obtained considering the real water needs of locally cultivated products and the efficiency of the irrigation technique applied. The results clearly show the advantage in energy and water savings of the integrated design approach, which recognises synergies and trade-offs under the environmental and economic point of view. Moreover, considering only the integrated approach, some other comparisons are carried out from a technological perspective. Different irrigation techniques are evaluated and compared in terms of energy request and water consumption, to underline how energy and irrigation are further linked.

Finally, considering the three design approach differences in results and the strong evidence of the interconnections between energy and irrigation needs derived from the technological comparisons, the integrated approach is expressed in general terms.

Key words: energy; irrigation; load curve calculation; water savings; Eritrea.

SOMMARIO

Acqua ed energia sono strettamente interconnesse nel settore agricolo. Le colture necessitano di acqua per crescere, acqua che richiede un dispendio energetico per essere pompata e distribuita. È possibile migliorare la resa dei prodotti agricoli, in termini di quantità e qualità, grazie a un uso consapevole delle risorse idriche e a una produzione sostenibile di energia elettrica. Sebbene il settore agricolo sia cambiato notevolmente negli ultimi anni, questi cambiamenti non sono uniformi a livello mondiale. Fenomeni globali di cambiamenti climatici, land grabbing e urbanizzazione incontrollata rendono sempre meno sostenibile lo sfruttamento delle risorse naturali, in particolare nei paesi in via di sviluppo. Le maggiori inefficienze a livello energetico e di utilizzo delle risorse idriche nel settore agricolo si rilevano proprio nei paesi dove non sono garantiti l'accesso all'energia e la sicurezza alimentare.

Al fine di comprovare i legami tra prelievi idrici, metodi di irrigazione impiegati e richiesta energetica, si presenta un caso studio relativo a una concessione agricola in una zona rurale dell'Eritrea. La situazione attuale del consumo energetico e idrico del sistema di irrigazione impiegato, che è stato osservato durante l'esperienza sul campo dell'autrice, è stata confrontata con due approcci per la progettazione di un sistema energetico più performante. Il primo è un dimensionamento basato su una domanda energetica stimata senza considerare il calcolo diretto dei fabbisogni idrici delle coltivazioni locali. Il secondo approccio, invece, prevede la progettazione integrata del sistema energetico e idrico, costruendo la curva di carico energetica necessaria al pompaggio e alla distribuzione dell'acqua irrigua, passando per il calcolo dei fabbisogni idrici reali dei prodotti coltivati localmente e per l'efficienza del metodo irriguo impiegato. La progettazione integrata riconosce le sinergie e i trade-off del sistema energetico e di quello irriguo, mostrando nei diversi confronti il possibile risparmio di risorse naturali. Inoltre, all'interno dell'approccio integrato, sono confrontate diverse tecnologie di irrigazione. I risultati mostrano le differenze tra diverse tecniche irrigue in termini di richiesta energetica e idrica, a sottolineare il loro legame.

Infine, considerando i risultati dei confronti tra i tre approcci e l'evidente interconnessione tra energia e fabbisogni irrigui, l'approccio integrato è espresso in termini generali.

Parole chiave: energia; irrigazione; curva di carico; risparmio idrico; Eritrea.

ESTRATTO IN LINGUA ITALIANA

Capitolo 1 Introduzione e motivazioni

Lo scopo della tesi è la progettazione integrata del sistema acqua-energia per impianti di irrigazione in concessioni agricole in paesi in via di sviluppo. Spesso, infatti, la progettazione energetica in questi contesti si basa su assunzioni riguardo la potenza nominale di impianto che derivano da questionari o ipotesi che potrebbero discostarsi dai fabbisogni reali delle fattorie, sia in termini energetici che in termini di fabbisogni idrici delle colture.

Acqua ed energia sono strettamente interconnesse, soprattutto nel settore agroalimentare. Il settore agricolo è attualmente il maggior utilizzatore di risorse idriche a livello globale, impiegando il 69% del totale dei prelievi di acqua. L'approvvigionamento idrico delle città ne impiega il 12% e i prelievi del settore industriale il 19%. La produzione di colture agricole è al cento di uno scenario in mutazione: fenomeni globali di land grabbing hanno reso sempre più complessa la gestione delle risorse naturali, i cambiamenti delle abitudini alimentari mondiali hanno modificato la catena di produzione così come la crescita della popolazione ha incrementato la domanda di prodotti alimentari. Mentre nei paesi industrializzati l'agricoltura è diventata di tipo intensivo, utilizzando tecnologie sempre più moderne e sviluppandone di nuove per il monitoraggio delle rese agricole, nei paesi in via di sviluppo i metodi di produzione agricola hanno subito cambiamenti meno drastici e l'agricoltura di tipo tradizionale resta ancora tra le più diffuse.

Capitolo 2 Acqua ed energia nell'agricoltura: situazione attuale

Il contesto in cui si agisce al fine di aumentare la resa agricola delle colture è frammentato. Si vuole focalizzare l'attenzione sullo stato attuale di comprensione e gestione di dimensioni sostanzialmente differenti, come acqua ed energia, che sfruttano le medesime risorse naturali, relativamente al caso di economie emergenti.

Le risorse idriche globali sono le risorse rinnovate dal ciclo dell'acqua, di cui alcune, accessibili fisicamente, sono utilizzate dall'ambiente, quindi non rinnovabili: circa il 56% delle precipitazioni annue è evapo-traspirato da foreste naturali, il 5% da agricoltura pluviale. Il restante 39% costituisce le risorse idriche disponibili rinnovabili, sia superficiali (fiumi, laghi, nevi perenni), che sotterranee. La distribuzione, inoltre, non è geograficamente uniforme, esistono differenze considerevoli tra un continente e l'altro. Ad esempio, in America Latina le precipitazioni possono raggiungere i 1600mm/anno contro i 96mm/anno delle regioni del Nord Africa. Anche le condizioni climatiche rivestono un ruolo decisivo, evidente se si considera che Europa e Africa Sub-Sahariana misurano precipitazioni simili in valore assoluto, ma le maggiori temperature nel continente africano comportano elevate perdite di acqua per evaporazione. Un altro importante fattore è lo sfruttamento delle falde acquifere, che ha un grande potenziale in paesi in via di sviluppo, ma al contempo rischia di mettere a repentaglio la stabilità e la sostenibilità delle sfruttamento stesso.

Non solo la distribuzione di risorse idriche naturali non è uniforme a livello geografico, ma lo è anche l'impiego di tali risorse nel settore agricolo. I prelievi di acqua utilizzati in agricoltura dipendono dal tipo di colture, dal clima, dalle proprietà fisiche del suolo, dalle tecniche irrigue, dal livello tecnologico impiegato nella coltivazione. Anche in questo caso, esistono delle differenze tra paesi in via di sviluppo e paesi sviluppati. In termini di efficienza di irrigazione, definita come rapporto tra i fabbisogni idrici delle colture agricole e il volume effettivo di acqua prelevata, i paesi Low Income si attestano su un valore medio del 48%, i Middle Income sul 56%, mentre i paesi High Income superano il 60%. Le maggiori inefficienze si presentano proprio nei paesi in cui la food security non è garantita universalmente.

L'efficienza irrigua deriva dal prodotto di due componenti: l'efficienza di campo e l'efficienza di distribuzione. Per quanto riguarda i sistemi di distribuzione, nei paesi in via di sviluppo è largamente diffuso il sistema a canali in terra, per via della semplicità di realizzazione. La sua efficienza, tuttavia, è del 60%-80% a causa delle notevoli perdite che intercorrono prima che l'acqua raggiunga il punto di interesse. Il valore dipende dalla lunghezza del canale e dal tipo di terreno. Una possibile variante dei canali in terra è data dai canali rivestiti, la cui efficienza è molto maggiore, circa 95%, indipendentemente da lunghezza di percorrenza e tipo di terreno. La stessa efficienza di distribuzione è garantita da un sistema di distribuzione intubato, dove l'acqua è trasportata fino al punto di consegna attraverso una rete di tubi. L' efficienza di campo, invece, dipende dal metodo irriguo utilizzato. L'acqua, una volta raggiunto il punto da irrigare, è soggetta a perdite per ruscellamento e per percolazione profonda. Irrigazione superficiale, irrigazione per aspersione, irrigazione a goccia sono le tecniche sotto cui vengono raggruppati i metodi di applicazione dell'acqua e ognuna di esse presenta un'efficienza di campo diversa. Il pompaggio dell'acqua irrigua può avvenire con diverse tecnologie di pompe, che possono servire tipi di pozzo differenti. Conoscendo il modo in cui l'acqua è soggetta a inefficienze, è possibile migliorare notevolmente il suo impiego nel settore agricolo.

Durante la fase di progettazione di un sistema irriguo dal punto di vista energetico, l'assenza di uno studio preliminare dei fabbisogni idrici colturali e del sistema di irrigazione più adatto al contesto, può comportare una disconnessione tra bisogni reali delle colture e bisogni attesi, sia dal punto di vista idrico che energetico. L'energia necessaria al pompaggio e alla distribuzione dell'acqua nei campi è direttamente collegata al volume di acqua necessario alle colture e anche al tipo ti tecnica irrigua applicata, da cui dipende il valore lordo di acqua da distribuire. Se si considerano sistemi di produzione di energia decentralizzati dedicati a sistemi irrigui, il rischio di sovradimensionare o sottodimensionare l'impianto se non si considerano i legami con la dimensione idrica, è notevole e non sostenibile, né economicamente né per quanto riguarda l'aspetto ambientale. Molto spesso in Africa, Asia e India, la produzione di energia in sistemi decentralizzati utilizza generatori diesel, che tuttavia non sono la soluzione più efficace in contesti dove le energie rinnovabili potrebbero rappresentare un'alternativa vantaggiosa. La grande disponibilità di fonti di energia rinnovabile, la loro convenienza economica rispetto ai generatori diesel, l'indipendenza che permettono da qualsiasi tipo di combustibile, spesso dispendioso e difficile da reperire, lascia intravedere incredibili opportunità e potenzialità per il settore agricolo in paesi in via di sviluppo.

Capitolo 3 Stato dell'arte: simulazioni energetiche e calcolo dei fabbisogni idrici colturali

Al fine di valutare la fattibilità tecnico-economica per un sistema energetico, che sia rinnovabile o ibrido, distribuito o decentralizzato, è necessario dimensionare i componenti e simulare il funzionamento complessivo della soluzione elaborata tramite un software. Tra i vari strumenti disponibili, un primo dimensionamento può essere realizzato tramite HOMER Pro di HOMER Energy. Il programma richiede come input la curva di carico energetica per un anno di funzionamento, i componenti del sistema e i relativi parametri di costi di investimento ed esercizio, le risorse energetiche locali, oltre a informazioni generali sulla vita utile dell'impianto, tasso di interesse, percentuale ammissibile di carico insoddisfatto etc. Se il sistema rispetta i vincoli imposti, la simulazione calcola i flussi energetici e il costo totale di investimento e di esercizio per tutta la vita utile del sistema.

Per quanto riguarda la determinazione dei fabbisogni idrici colturali, anche in questo caso è necessario un programma o un modello di simulazione. Il fabbisogno idrico di una determinata coltura, infatti, dipende da molti fattori e varia durante le fasi di crescita della pianta e in base a cambiamenti climatici stagionali. Per affrontare il calcolo, è possibile ricorrere al software open source elaborato dalla FAO, CROPWAT 8.0. Il software in un primo momento calcola l'Evapotraspirazione potenziale, un parametro climatico ottenuto tramite il metodo Penman-Monteith. Tale valore deriva da altri parametri climatici, quali temperatura e umidità dell'aria, velocità del vento, irradiazione solare. L'evapotraspirazione potenziale rappresenta la quantità di acqua che evapora e traspira da una superficie di riferimento, arbitrariamente assegnata come una superficie ricoperta da erba. Il parametro, quindi, risulta indipendente dal tipo di tipo di prodotto agricolo coltivato. Successivamente, tramite l'approccio del coefficiente colturale, CROPWAT ricava l'evapotraspirazione colturale in condizioni di assenza di stress idrico, specifica per ogni tipo di coltura inserito nel programma. In base agli alti parametri inseriti, quali precipitazioni, schema colturale, date di semina, informazioni sul tipo di suolo, il calcolo produce il fabbisogno idrico colturale in $\left[\frac{mm}{day}\right]$ per ogni coltura. A questo punto, conoscendo il limite di umidità del suolo oltre il quale la specifica coltura incorre in stress idrico, si può risalire al volume di irrigazione, al turno irriguo (giorni che intercorrono tra due adacquate successive), alla dotazione specifica ovvero la portata di acqua da distribuire per unità di superficie espressa in $\left[\frac{l}{s\,ha}\right]$ e infine, conoscendo la superficie coltivata e il tempo di consegna, si risale alla richiesta idrica della coltura in $\left[\frac{l}{s}\right]$.

Capitolo 4 Il caso studio

Le considerazioni riguardo le sinergie e i trade-off tra acqua ed energia nella produzione di beni alimentari, vengono riproposte in un caso studio, al fine di evidenziare la valenza pratica della trattazione teorica. Il contesto di riferimento è un podere di circa 10ha in una zona rurale dell'Eritrea, non collegata alla rete elettrica nazionale. Lo scopo è quello di studiare l'attuale consumo energetico e sfruttamento delle risorse idriche per confrontarlo con due approcci al dimensionamento di un sistema energetico più effciente:

- Una progettazione basata sulla domanda energetica, in cui i contadini e il progettista elaborano una possibile curva di carico dell'impianto energetico, senza considerare né uno studio delle risorse idriche locali, né una valutazione del fabbisogno idrico delle colture esistenti;
- Una progettazione integrata del sistema energetico e irriguo, che tenga conto, nel calcolo della curva di carico energetica, della disponibilità di risorse locali, dei reali fabbisogni idrici delle colture del podere, del sistema o dei sistemi di irrigazione più adatti alla distribuzione di acqua.

Per lo studio della situazione attuale, durante la visita alla "Concessione Agricola Ferrando Ezechiele", sono stati raccolti dati relativi alla potenza nominale delle motopompe alimentate a diesel, durata di esercizio, frequenza di irrigazione durante la stagione delle piogge e durante quella secca, costo del combustibile, efficienza del motore in $\left[\frac{l_{fuel}}{h}\right]$. Per il dimensionamento energetico secondo l'approccio basato solo sul lato energetico, la curva di carico energetica è valutata insieme ai gestori della concessione e rappresenta la stima dei fabbisogni ricavata senza considerare il calcolo della richiesta idrica delle colture. Nell'approccio integrato, invece, la curva di carico è calcolata solo in ultima analisi, dopo una serie di fasi di raccolta di dati, di calcolo dei fabbisogni idrici colturali, di elaborazione di un sistema di irrigazione e di calcolo delle perdite di carico.

La fase iniziale dell'approccio integrato ha riguardato lo studio della risorsa idrica localmente disponibile, rappresentata da un fiume stagionale da cui si estrae l'acqua per l'irrigazione mediante tre pozzi aperti. Grazie al supporto tecnico di due funzionari del Ministero della Terra, dell'Acqua e dell'Ambiente del governo eritreo, è stata condotta una prova di pozzo per valutare la disponibilità di acqua e i tempi di ristabilimento del livello originario di falda. Per il caso specifico, il test non è completo per mancanza di dati storici, ma la valutazione seppur parziale, ha contribuito alla formulazione di alcune ipotesi nel corso dell'analisi. Insieme ai gestori della concessione agricola, sono stati realizzati gli schemi di colture nei campi, le cui dimensioni sono state misurate e riprodotte attraverso un programma CAD. I dati climatici e quelli relativi alle precipitazioni sono stati ricavati da database online, mentre i dati relativi al suolo sono stati valutati tramite l'analisi della composizione del terreno e tramite un programma di calcolo, Soil Water Charcteristics. Grazie al software CROPWAT 8.0, sono stati calcolati i fabbisogni idrici colturali, per tutte le colture ipotizzate dai gestori della concessione e da tali valori, insieme ai parametri legati al tipo di suolo, si è ottenuta la portata di acqua da fornire alle colture per ogni mese dell'anno, al netto delle perdite del sistema di irrigazione. Il metodo irriguo utilizzato nell'approccio integrato per i confronti con la situazione attuale e l'approccio al dimensionamento basato solo sul lato energetico, è il metodo di irrigazione tradizionale, ovvero irrigazione per scorrimento con canali di distribuzione in terra. Il motivo principale è che, essendo il metodo meno efficiente, è quello che impiega una maggior quantità di acqua e potenzialmente di energia, rispetto agli altri due metodi scelti nell'approccio integrato (irrigazione intubata e per aspersione). Pertanto, si presuppone che gli altri metodi possano ottenere unicamente risultati migliori. Nell'ambito dell'approccio integrato di progettazione energetica e irrigua, sono stati realizzati ulteriori analisi e confronti tra il metodo tradizionale di irrigazione e gli altri due metodi, scelti valutando le condizioni geologiche del sito, il tipo di suolo e di colture presenti. Gli altri due metodi irrigui selezionati per la determinazione delle curve di carico energetiche da simulare, sono: irrigazione in tubi a bassa pressione e irrigazione per aspersione. L'irrigazione a goccia, che è un sistema fisso, è stata esclusa dall'analisi per via della rotazione annuale delle colture prevista dai gestori del podere e per via della scarsa presenza di colture fisse. La progettazione prosegue con la definizione, per ogni tipo di irrigazione, degli schemi di distribuzione, ottimizzando i diametri dei tubi di adduzione e verificando che le pressioni operative rientrino nei range stabiliti.

I confronti tra gli approcci, in particolare tra la situazione attuale, la progettazione basata sulla domanda energetica e la progettazione integrata sono stati in netto favore del terzo approccio, dal punto di vista del carico energetico richiesto, della potenza installata, del Net Present Cost dell'impianto energetico e delle emissioni prodotte.

I confronti proseguono all'interno dell'approccio integrato, tra i diversi accoppiamenti tra sistema di irrigazione e sistema energetico. Si tratta, quindi, di confronti tecnologici tra i diversi metodi irrigui scelti. Le configurazioni di carico richiesto sono due:

- Configurazione A, in cui si prevede l'utilizzo di serbatoi di acqua, caricati secondo una richiesta giornaliera costante in base al mese dell'anno. I serbatoi permettono di disaccoppiare la fase di pompaggio da quella di distribuzione. L'irrigazione, infatti, non avviene giornalmente, ma segue un programma preciso, per cui attraverso i serbatoi si sfrutta l'energia rinnovabile quando è disponibile, inoltre le taglie delle pompe e quindi dell'impianto energetico si riducono notevolmente;
- Configurazione B, in cui pompaggio e distribuzione avvengono simultaneamente per evitare i costi dei serbatoi d'acqua. Le potenze installate sono maggiori, ma si riducono notevolmente i costi di investimento.

Dai confronti deriva che la configurazione A comporta costi di investimento insostenibili per il contesto in analisi, mentre la configurazione B, sebbene presenti potenze installate maggiori, è vantaggiosa dal punto di vista economico. Riguardo il consumo energetico atteso, l'impiego del metodo di irrigazione tradizionale che movimenta un volume d'acqua maggiore, non è sempre la soluzione più energivora, infatti tecnologie più performanti possono richiedere livelli di pressione maggiore, come avviene nel caso di irrigazione per aspersione. Ad ogni modo, l'incremento di energia richiesta non è paragonabile alla domanda energetica nell' approccio basato sulla situazione attuale e sulla domanda energetica disaccoppiata da quella idrica. La migliore soluzione tecnologica nell'approccio integrato, in termini economici, è quella che prevede l'utilizzo di un sistema di irrigazione intubato. La scelta finale deriva da un'analisi del NPC, dell'efficienza irrigua e della potenza installata, oltre che della domanda di carico insoddisfatta e dell'energia prodotta in eccesso.

Capitolo 5 Conclusioni

Il caso studio valida l'ipotesi iniziale per cui riconoscere le interconnessioni tra fabbisogni idrici colturali e fabbisogni energetici può portare a notevoli vantaggi nel dimensionamento sia del sistema energetico che del sistema di distribuzione idrica. Conferma, quindi, il vantaggio strategico nella gestione integrata di risorse comuni per ambiti quali energia e acqua, in relazione alla produzione agricola. Inefficienze energetiche e irrigue non sono sostenibili in contesti già instabili a livello ambientale.

L'approccio integrato è, dunque, riproposto in termini generali, evidenziando come la dotazione di risorse idriche locali sia il maggior vincolo, mentre la principale variabile sia il fabbisogno idrico colturale. Da questo valore, è possibile calcolare una curva di carico energetica basta sull'effettiva richiesta idrica delle colture, passando attraverso lo studio delle possibili tecniche di irrigazione, al fine di determinare la soluzione che meglio si adatta al contesto locale.

Capitolo 6 Sviluppi futuri

L'assenza di dati storici, ad esempio riguardo la disponibilità di acqua o delle risorse energetiche locali, limita la possibilità di realizzare analisi complete e realistiche. Tuttavia, in caso di scarsa disponibilità di informazioni è possibile utilizzare dati ad esse collegate o approssimativamente dello stesso contenuto informativo.

Limitatamente all'impiego di tecnologie più evolute in ambito irriguo, si possono integrare le tecniche con i più nuovi dispositivi, al fine di consentire un monitoraggio immediato e più completo.

Per quanto riguarda l'aspetto finanziario, invece, l'obiettivo principale della tesi si concentra su una singola farm, la quale si inserisce in un contesto più ampio, in una comunità di circa un migliaio di abitanti, le cui attività principali si basano su agricoltura e pastorizia. L’espansione del progetto all’intera comunità rurale che condivide e utilizza le stesse risorse idriche, può costituire un incentivo finanziario per via del fatto che diversi stakeholder sarebbero coinvolti: i contadini, il cui interesse sarebbe mosso in primo luogo dall’aumento delle rese dei prodotti agricoli coltivati grazie allo sfruttamento più efficiente delle risorse idriche ed energetiche, ma anche il governo locale e le ONG eventualmente coinvolte, il cui obiettivo principale sarebbe la conservazione ambientale.

Sommario

Chapter 1 INTRODUCTION AND MOTIVATIONS

The idea of this thesis starts from my Eritrean origins. During the years I spent studying Energy Engineering, I had the chance to be personally involved into the changing framework of a complex country such as Eritrea. Observing the energy and water constraints the country has been limited by and how they remarkably changed in recent years, I was interested in understanding the Eritrea's plan to face its new challenges, in particular in the agricultural sector. Unfortunately, there were many aspects that were not changing at the same level of natural changes, especially in rural areas where agriculture was the main occupation. Water withdrawals for agricultural purpose remained at the historical rate and the access to modern energy and its services was not a central issue in that context. Energy and water are interconnected in several ways in food production: crops growth requires water, which needs energy to be pumped and distributed. Agriculture could be strongly enhanced in terms of quality and quantity of food products through a conscious use of water and a sustainable energy generation.

The thesis aims to develop an integrated design of energy-water system for irrigation purpose, in order to evaluate the real needs of an agricultural farm in terms of water – depending on cultivated crops in a specific environment– and energy – to supply the required water. To develop this approach, a specific case study of a farm in rural area in Eritrea is studied. The integrated approach is compared with the current energy and water consumptions of the farm and it is compared also with a demand driven design approach, where the energy load is evaluated through a survey filled by farmers. In the demand driven design the energy system is studied in a separate way from the water and irrigation system, without taking into consideration their linkages.

Moreover, considering only the integrated approach, some other comparisons are carried out from a technological point of view. Different irrigation techniques are evaluated and compared in terms of energy request and water consumption, to underline how energy and irrigation are further linked.

Finally, considering the three design approach differences in results and the strong evidence of the interconnections between energy and irrigation needs derived from the technological comparisons, the integrated approach is expressed in general terms.

In the following section of this chapter, Water Energy Food (WEF) Nexus is introduced and analysed in a global prospection, focusing on agricultural sector.

1.1. Water Food Energy Nexus

Water, energy and food are inextricably linked. Water is a basic input for the production of agricultural goods in fields and along the entire food processing chain. Energy is required both for water withdrawal and food production: to pump water from groundwater or surface sources, to power tractors and irrigation machineries, to process and transport agricultural goods. Furthermore, water is a pillar of human well-being and environmental stability. Without water and access to it, there is no food security and no human dignity. The same amount of water is available on the Earth today as in the past, but global warming makes water availability more uncertain.

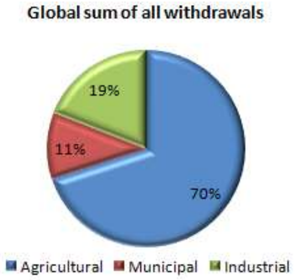
Access to water is a socio-economic and political challenge. Demographic trends, food preferences, differences in diets, cultural and social beliefs and behaviours, but also international and regional trade, markets and prices, industrial development are strong drivers behind the expansion of agriculture and the current water predicaments. Food systems contribute significantly to global warming, which modifies rainfall patterns and evapo-transpiration rates [1].

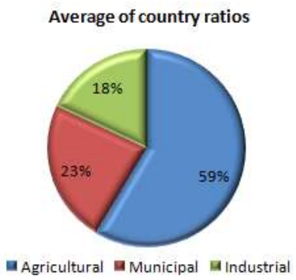
Only 2.5% of the water stored on Earth is freshwater, the rest is saline water and oceans water. Of the total freshwater, 0.3% is surface water (lakes, rivers), while 30.8% is groundwater, which includes soil moisture, permafrost, and 68.9% consists of glaciers and permanent snow covers.

The amount of precipitation per year is almost 110000km^3, but only the renewable freshwater could be considered interesting for water *withdrawals*. It means that some water is removed from superficial sources or from aquifers in order to meet human needs. Most of the withdrawn water is returned to the environment some period later, but quality may be lower than the moment when it was firstly removed. There are fundamentally three types of withdrawals:

- Agricultural – including irrigation and livestock
- Municipal – including domestic
- Industrial

Agriculture is currently the largest user of water at global level, accounting for 69% of total withdrawal. Municipal withdrawals count for 12% and industrial for 19%. These numbers are strongly affected by bias error due to countries' marked differences in water consumption. To overcome this inconvenient, the ratios in each type of withdrawal could be averaged for any given country, obtaining the distribution reported in the figure below: 59% agricultural withdrawal, 23% municipal, 18% industrial.





The water withdrawal ratios vary much between regions, going from 91%-7%-2% for respectively agricultural, municipal and industrial water withdrawals in South Asia to 5%-23%-73% in Western Europe [2]. The place of agriculture in the economy of a certain country is very important, there are countries that rely on agriculture for more than 70% of their GDP (Gross Domestic Product), as it happens in Sub-Saharan Africa [3], while in other industrialised countries the percentage of value added in GDP by this sector is very low. Considering all the variations the agricultural sector has suffered during last years, it is clear that geography plays a significant role in understanding how water is used in one country.

In recent years, indeed, changings in the way countries supply foodstuff for their population disrupted the agricultural scene. Until 2006, developed countries through multinational firms were involved only in food processing phases, as treatments, packaging and marketing, while production was left mainly to developing countries [4]. The reasons are several, but originally, due to post colonisation heritage, poorer countries wanted to lift their economy out of industrialised nations' control. In 2006, something changed and a huge amount of Foreign Direct Investments (FDI) was addressed to agricultural sector. Main determining factors were the increase in foodstuff prices and in return of investments in agriculture, behind a global increase of agricultural land value. Other variables pushed the interest in the agricultural sphere, such as the economic advantage deriving from product internalisation in opposition to the classical *contract farming.* The upturn in international food prices was surely the most representative proof that the market was moving forward a new direction, but it was accompanied by much higher price volatility than in the past [4]. New drivers emerged: certain agricultural product had a high demand that was not related to food security at all. One emblematic example is what happened with feedstock for biofuels production, in particular maize for ethanol, as a consequence of oil price record few years ago and environmental strategies carried on in developed world. This was the new gold rush, where land, especially intended for agricultural purposes, acted as the precious metal. The phenomenon is called *land grabbing* in a negative meaning, because of the contradictions it created. There is a massive overlap between land-grabbed countries and countries threaten by food insecurity, as it is shown in Figure 2 [5], where the target countries are mostly in Sub-Saharan Africa, Asia and South America.

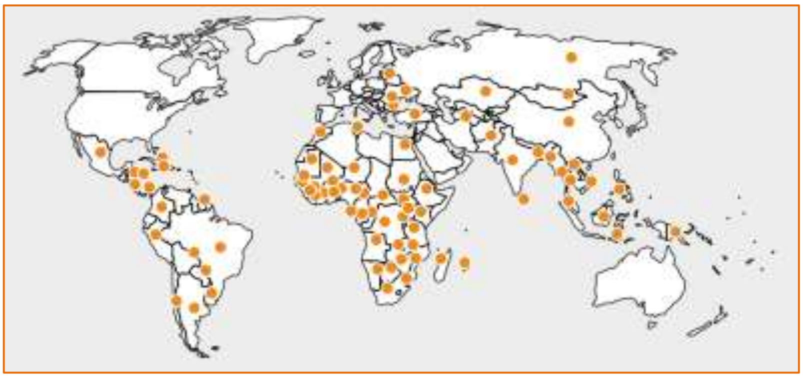


FIGURE 2 TARGET COUNTRIES

Although all these various ambiguities, there are also opportunities coming from policies of openness. Many developing countries have available land and it is suitable for cultivation, but still low productive. Consequently, this land has a high potential and FDI focused on agriculture could be a successful strategy. There would be also collateral positive aspects, as infrastructure improvements, local capacity building and even environmental protection, behind financial support. Such an investment could mean a threshold in agriculture, leading to a more modern and technological based food sector. It could represent an incentive for the enhancement of expertise and capabilities.

It is still a complex and multiple-side context, where loosing land control by governments is risky and often dangerous for population. The ease to arise social issues as well as instabilities in job opportunities or environmental degradation due to leasing contracts should be carefully analysed. Negotiation between local farmers and foreign governments would only perpetuate the current imbalanced situation, where players have very different roles, while an international rule - still missing - could better keep local land rights.

The rapid changes regard also the socioeconomic terms and the relative attitudes, which have direct impact on water, resource exploitation and environment. Human capacity to modify the Earth’s natural course is at par with geological forces, with a great responsibility toward the future. The circulation of water in the hydrogeological system is exacerbate by global warming, which makes the water flow to the atmosphere faster with a consequent increase in temperature. Generally, to predict the length of cultivation seasons is harder, with more intense precipitation during off-season and less water when particularly needed. Even the way people use land affect water flows. Tilling practices, the type of crops cultivated, soil texture and organic content affect water-holding capacity. Otherwise, feeding the planet is at the centre of global debate not only for the feasibility of the issue, but also for its implications on human health through healthy foods and sustainable environment exploitation. Population is growing fast worldwide, but numbers are changing also in average daily per capita food calories. In 1961, global average supply was 2194kcal/day/person (338 and 1856 animal and vegetal calories); in 2011, it increased to 2868kcal/day/person (507 and 2362 animal and vegetal calories) according to [6]. This is an aggregated number, but distribution is not uniform, as shown in Figure 3.

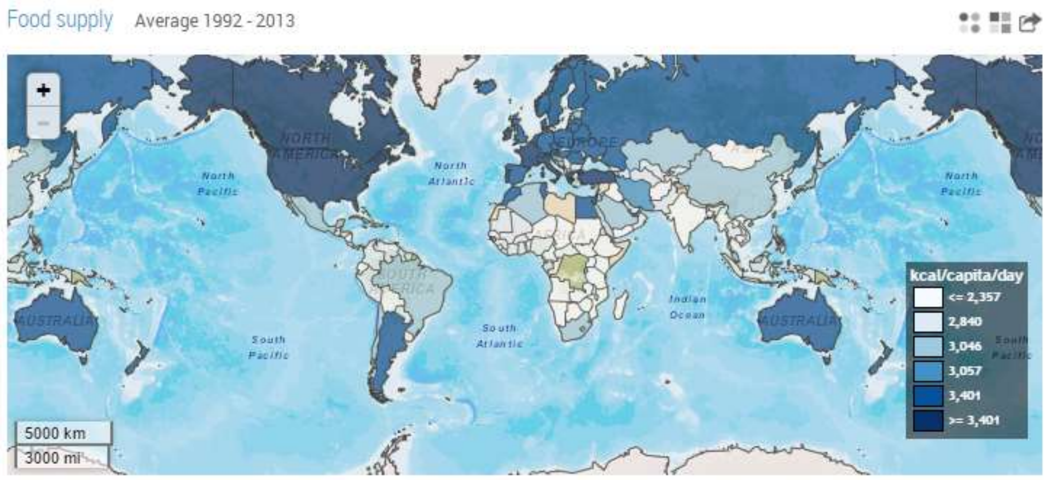


FIGURE 3 FOOD SUPPLY DISTRIBUTION

The food production and supply chain accounts for about 30% of total global energy consumption [7]. There are many synergies and trade-offs between water and energy use and food production. Using water to irrigate crops might promote food production but it can also reduce river flows and hydropower potential. Nearly half of United States' water withdrawals are used for thermoelectric power plant cooling. There are differences between the fuel used: coal and nuclear consume respectively 2 and 2.5 times more water than natural gas, while renewable sources like solar or wind plants virtually does not use water at all. Lands are devolved to biofuels production to reduce greenhouse emissions, but growing bioenergy crops under irrigated agriculture can increase overall water withdrawals and jeopardise food security. Converting surface irrigation into high efficiency pressurised irrigation may save water but may also result in higher energy use. Recognising these synergies and balancing these trade-offs is central to jointly ensure water, energy and food security. The three systems of water, food and energy are in conflict with one another and under strain due to climate and extreme weather events, poor resource planning and even population growth.

Urbanisation and expansion of industry and service sectors imply a new mix in the demand and competition for water and energy. Crop production, livestock, fisheries and forestry still continue to need large areas with fertile soils, significant volumes of water and energy. National and local governments in partnership with relevant organisations and institutions, including considerable user groups should coordinate the use of water, energy and land through suitable institutional arrangements. Effective co-governance of these resources presumes inclusion of environmental concerns and socioeconomic objectives, e.g. job and income generation. Governance of such complex systems requires a combination of flexibility, big picture vision and strong alliances and it must be based on evidence and tested for realistic and desirable scenarios. At country's level, fragmented sectoral responsibilities, lack of coordination and differences between laws and regulatory frameworks may lead to misaligned incentives.

For these reasons, approaching problems linked to water or food or energy management could be more complete if thought as a whole.

Main problems of rural population involved in agriculture in developing countries are linked to water management and energy access. After some research activities, it was clear that in these countries, water management is not a priority, although in many cases, i.e. in Sub Saharan Africa, farmers are facing a hard challenge against physical and economical water scarcity. The following section was conceived to understand water waste and excessive energy consumption linked to food production. In agricultural estates, water management is strictly linked to crop yields, but also to quality targets of local markets.

Every food product uses a quantity of water to grow. Considering the Nexus especially but not limited to the agricultural sphere, some considerations are significant. For instance, comparing products, in particular foods, in terms of their water footprint would lead to better understand their needs and the energy they require. The water footprint is a measure of the amount of water needed to produce each good and service we use, or "[…] a measure of humanity's appropriation of fresh water in volumes of water consumed and/or polluted". It has three components according to [8]: green, blue and grey:

- *Green water footprint* is water from precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants. It is particularly relevant for agricultural, horticultural and forestry products.
- *Blue water footprint* is water that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time. Irrigated agriculture, industry and domestic water use can each have a blue water footprint.
- *Grey water footprint* is the amount of fresh water required to assimilate pollutants to meet specific water quality standards. The grey water footprint considers point-source pollution discharged to a freshwater resource directly through a pipe or indirectly through runoff or leaching from the soil, impervious surfaces, or other diffuse sources.

Water problems are often connected to the structure of global economy. Many countries have significantly externalised their water footprint, importing water-intensive goods from elsewhere. The exporting regions, unfortunately, are the same regions where water governance and conservation mechanisms are lacking. Examples of water footprints are reported in Table 1.

	Total footprint	Green [%]	Blue [%]	Grey [%]
Apple	822 litre/kg	68	17	15
Banana	790 litre/kg	84	12	4
Tomato	214 litre/kg	50	30	20
Orange	560 litre/kg	72	20	8
Potato	287 litre/kg	66	11	23
Rice	2497 litre/kg	68	20	12
Bio-ethanol	2854 litre-w/litre-eth	77	7	16
Beef	15415 litre/kg	94	4	2

TABLE 1 WATER FOOTPRINT OF SOME FOODS

Unfortunately, water is not unlimited. The importance of groundwater as resource has grown during last decades. Surface water is already exploited, especially since cheap pumping technologies are available and because of the lack of regulation in many developing countries. Small-scale device can be easily moved from one place to another and it is significant in their imprint on water. In India alone, the number of private wells was estimated at close to 20 million [9] while in Africa irrigation development is much slower. In 2014, less than 5% of the cultivated area is irrigated [10], but groundwater in Sub-Saharan Africa may be twenty times more than that superficially available, according to [11]. It is more and more necessary to rethink the rationing and optimization of water usage in all its destinations. Water savings in agriculture depends on frequency of irrigation actions, on maintenance, on the number of users of the same water source and their ability to preserve it. A great importance should be given to farmers' awareness and knowledge about cropping systems and irrigations practices, behind the local climatic changes. The global food system, indeed, includes deforestation in order to make way for crops and cattle and it causes about one third of total greenhouse emissions. To exactly tackle all the issues about food and climate change connections, it should be taken into consideration that our food system is totally different from the past. Now, it is fossil fuels dependant, the production is no more locally based and agriculture is more and more modern, affecting greenhouse emissions.

The importance of water for plant growing, however, is many-sided. It is the main reagent in multiple chemical processes inside vegetal textures; it allows maintaining cells turgor; it guarantees the internal temperature control (thermoregulation) and finally it conveys nutrients that have to be up taken. Inside water, there are soil minerals that are required for plant growth. If the plant suffers water stress during its earlier stages of growth, it could damage both quality of products and quantity of harvest. One of the major problems about agriculture is the lack of water during the hottest period, when rainfalls are lower in quantity. Irrigation is an indispensable practice because it makes the water content inside soils constant in order to limit water stress for plants. Sometimes, irrigation performs other functions: control of insects, fertilizers distributing, leaching action for salty soils, pH control and temperature control.

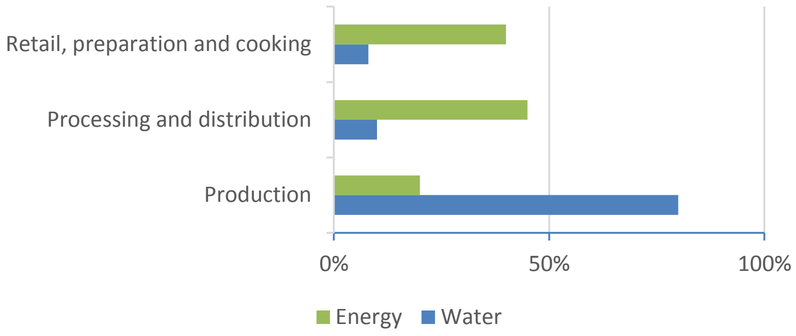
Water could be better used to enhance crop yield and products stabilisation, up to considering second harvesting possibilities, or furthermore augmenting the number of crops. However, products quality is influenced too, by modifying external shape and colour, organoleptic characteristics, sugar content and protein concentration or even shelf life.

Once the importance of irrigation is clear, the attention should move on the other issue in agricultural water systems, the *energy*. Industrial and non-industrial agriculture consumes fossil fuels for several purposes: fertilizers production, mostly synthetic which require significant energy input firstly in terms of natural gas; water moving and pumping; farm equipment, with machineries that runs on gasoline and diesel, or electric device as fans, pumps, etc.; finally, processing, packaging and transportation of foods. Despite the challenges posed by the energy-intensive nature of agriculture, the prudent use of natural resources and new technologies can enlarge the long-term sustainability of food production.

Nevertheless, there are many interconnections between energy and food sector and the more they are understood, the better their synergies are exploited. There are opportunities that can overcome threats, as smart policies, new dietary choices and technologies for business with the aim to solve both energy and food problems. Not only the known approaches, in recent times there is a debate about the comparison between local production and consumption of food (until now considered the most ecological solution) and on the other side, a huge large-scale industrialised agriculture [12]. Nothing is taken for granted, not even the advantage of producing and consuming foodstuff through a short chain supply.

Innovative techniques play a central role, for their possibility to solve the water problem, as it is for drip irrigation, which conserves water and the energy required to pump it. A great example of how smart irrigation could be a threshold for a country is the Israeli case. Since 1950s, Israelis have been finding brilliant ways to green their deserts and at the same time have shared their discoveries worldwide through channels like MASHAV, Israel’s Agency for International Development Cooperation and Ministry of Foreign Affairs. Drip irrigation, grain cocoons, biological pest control are few examples of their innovative and leader solutions for water savings and agricultural improvements. Their technologies are used in many developing countries, as it happens in Israel’s Tipa program, which has introduced drip irrigation to 700 Senegal subsistence farmers; or the Agricultural Knowledge On-Line (AKOL) project, that is a unique software to help producers grow fruit and vegetables, raise poultry and dairy cows, manage vineyards and make olive oil, developed in collaboration with IBM Global Tech Unit.

In Graph 1 is shown how energy and water use in food systems differ. Information about energy consumption derives from a FAO research [13]. The FAO study estimates energy consumption ‘from field to fork’ at around 32% of the total global end-use of energy. The energy use pattern is about the same for high GDP and low GDP countries.



GRAPH 1 SHARE OF INPUT IN FOOD SYSTEM

Efforts to improve energy use efficiency in food production may have limited effects on total energy use in food systems whereas water use in production could make a strong difference. Both improvements could lead to a new scenario. Beside the trade-off and competition for resources, this is the opportunity to rethink current practices, policies and governance arrangements to identify synergetic uses across sectors. The study suggest a new approach to the Water-Food-Energy nexus, where managing the nexus is possible through dialogue between stakeholders. The dialogue starts collecting evidence, which is needed to inform and substantiate discussions on future scenarios and responses; scenarios provide the potential impacts of different responses.

The relationship between water efficiency and energy efficiency is a key factor when designing an irrigation scheme. Moving water is energy-intensive, but there are several opportunities to save water and even energy, with a practical effect in economical savings. It is essential that any improvement to an irrigation system balances water efficiency and energy efficiency. It would be equally disadvantageous to use an extremely efficient system in terms of water consumption but with high power request where energy availability is low or very expensive, nor to use a system with low energy demand but high water consumption rate in places where water is scarce. In some cases, there is a trade-off between water and energy savings, in others there is not and good practices in water management lead lower energy consumptions. It depends on irrigation techniques, on main components used such as pumps and pipes, on maintenance, on soil characteristics, on local water uses. There are other variables to consider: electricity is more cost-effective for pumping than diesel, but it is not obvious that it is locally available. Not only the access to electricity, but also the reliability of the grid plays an important role in the energy supply chain.

Chapter 2 WATER AND ENERGY IN AGRICULTURE: CURRENT SITUATION

Recently population growth, arable land and water limits have received increasing attention from the scientific community in order to deeply evaluate the problem of ensuring global food security. However, except from some discussions about the slowly developing agricultural systems of sub-Saharan Africa and their requirements [14], much of the attention in those and other features has focused on fertiliser uses, or biotechnology improvements, and on precision management of the large-scale agricultural systems typical of developed countries [15] [16].

The countries where hunger and malnutrition are most widespread, notably in Sub-Saharan Africa, face different challenges. To increase the availability of food in those places and the population's direct access to food, it will be necessary to increase yields and to distribute those yields more effectively. However, current average yields are so low that large relative increases, which would be sufficient to achieve food security for at least the next decade, can be reached through existing technologies [17]. For example, Malawi more than doubled its maize yields on the national scale in a very short time, three years, through the use of currently available improved seeds and fertilizers, supported by an input subsidy program provided by the national government and international organisations [18]. The Asian developing countries achieved substantial yield increases from green-revolution technologies during the 1960s to 1980s, but rates of gain in cereal yields have slowed markedly in the past 10 to 20 years [19], even though agricultural inputs such as nitrogen (N) and phosphorus (P) have continued to increase. For example, Chinese cereal grain yields increased by 10% from 1996 to 2005, whereas the use of chemical fertilizers increased by 51%. That large increase in inputs without a correspondingly increase in yields further decreased the already-low ratio of grain harvested to fertilizer applied in China. This nutrient imbalance drives environmental pollution problems, such as greenhouse gas emissions and soil acidification [20]. These problems have become increasingly severe in rapidly developing countries, and their consequences are meaningful on a global scale. For example, 80% of the global increase of N fertilizer consumption in the last 10 years came from China and India [21].

There are many frameworks aiming to intensify yield of specific crops, such as cereals or the major foodstuffs, paying attention to soil quality and precision agriculture, but there are few examples of how they can be developed and adapted across the huge amount of rural fields worldwide [19].

In the following sections, current practices and technologies are explained in order to better understand the pieces of the frame that includes water resources, their management, their usage in agriculture, the existing methods to irrigate a field, the linkages between energy and water in food production. All the treatment is focused on developing countries and it is possible to identify some overlapping features and possible synergies while describing two apparently separated dimensions, i.e. energy and water.

2.1. Local water resources

The term *water resources* does not refer to all exploitable flow, on the contrary it could contain flows that are not available to be used. Renewable water resources are inland water renewed by the global water cycle, as shown in Figure 4, they are the main sources of water but not all of these flows are effectively exploitable, for various reasons. Firstly, the exploitability of a natural resource as water depends on the site physical conditions of accessibility and it varies by use. Furthermore, part of the natural flow is used by environment, for biosphere needs and in-stream use. It should be taken into consideration that the water flow might not be consistent from season to season, or from year to year and this factor could make it difficult to capture water in an adequate way. Statistical data are fundamental and the data collection process should be continuous to make available a high reliable dataset and to obtain always better forecasts. Moreover, precipitation should ensure many functions. Of 110000km^3 (equivalent to 814 mm), the major part, i.e. 56%, is evapotranspired by forest and other natural landscapes, 5% by rain fed agriculture. The lasting 39% (or 42920 km$^{3)}$ are the worldwide available annual renewable freshwater resources, both surface and groundwater. In 2014, the freshwater was equal to 5800m^3 per person per year, or 16000 litres per person per day [2]. While it seems to be enormous, the amount of freshwater is very unevenly distributed and above all, a large part is not accessible.

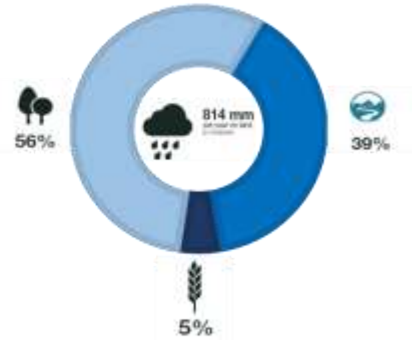


Figure 4 Water cycle

The American continent, which includes Latin America, is the most humid with a precipitation of 1104mm/year, but even between North and South America there are huge differences. The Caribbean region reaches 1600mm/year on average against only 637mm/year for the Northern America region. An interesting fact is that European continent receives less precipitation than the African continent, respectively 545mm/year against 677mm/year. The main reason is the presence of large arid areas of the Russian Federation. Precipitation in the northern Africa regions is 96mm/year, while the same amount of water, around 800mm/year, falls in Western and Central Europe and Sub-Saharan Africa regions. The strong difference is climate: moderate in Europe, while hot temperatures occur in large African regions where it results in remarkable water losses through high evaporation. However, there are particular cases, as Egypt: its annual precipitation are only 56mm/year, the lowest value worldwide, followed by Libya and Saudi Arabia, with 59mm/year. Nevertheless, the presence of the Nile brings a large amount of freshwater into Egypt, so that its renewable freshwater resources per person, 1900litres per day in 2013, is much higher than Libya or Saudi Arabia, which do not benefit from external rivers. Above all, countries with highest precipitation are usually islands, such as Costa Rica in Central America or Papua Nuova Guinea in Asia. There are 276 transboundary river basins worldwide that cover about half of the Earth surface and account for around 60% of freshwater flows. For instance, seven countries share the Amazon river in South America regions, eight the Mekong river basin in South and East Asia, eleven countries share the Nile in Africa, but the river crossing most countries is Danube in Europe, with its nineteen nations. Not only spatial differences, but also temporal differences, as it happens in India, where rainfall occurs under the influence of the southwest monsoon during October and November. During this period, about 70% up to 95% of the annual precipitation occurs.
A clear representation of spatial distribution is reported in Figure 5 with data aggregated by continent.

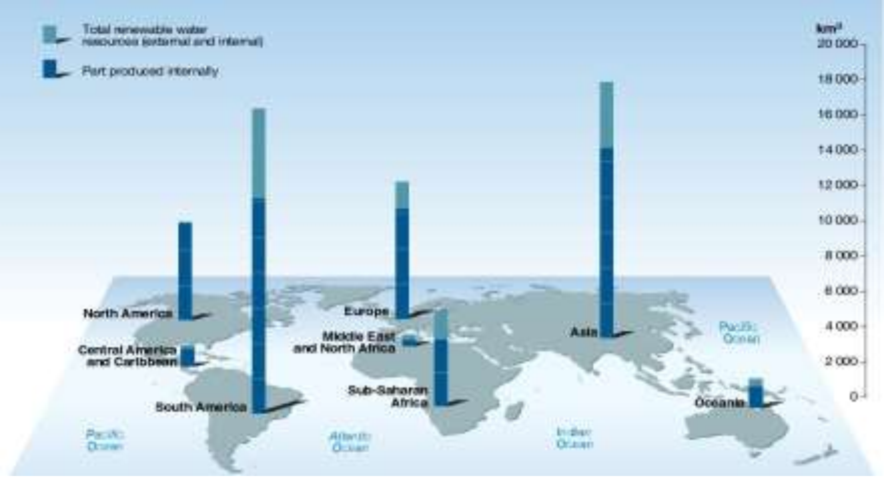


FIGURE 5 RENEWABLE WATER RESOURCES

Spatial distribution and water availability are affected by several factors, first in place population growth and economic development. More and more countries are reaching the limit which water can be sustainably delivered. Before introducing sustainability in water management and use, it is important to introduce another concept: *water scarcity*. It is an imbalance between supply and demand. It is a dynamic aspect because it intensifies with increasing users and with decreasing quality of the resource. The scarcity, as well as the sustainability, could occur at different dimensions, it could include scarcity in availability of freshwater of adequate quality, or scarcity in access to water services and infrastructures. In many regions, massive use of groundwater has been practised for some time for irrigation. Groundwater mining and the lack of adequate planning, legal frameworks and governance have opened a new debate on the sustainability of the intensive use of groundwater resources.

In most African areas, water is a serious constraint not only in relation to agricultural activities, but also considering human basic needs. That is the main reason why in this thesis there is a focus on water management and saving. The concept of *saving* itself is not as immediate as we could expect. Because of cultural heritage, or because of traditional management, or because of habits, innovation needs a bit of time to make a foothold in developing world as in the developed. That is why nothing could be excluded when trying to significantly change people's customs, neither cultural, social, environmental nor human aspects. They all are part of the long-term impact.

Talking about world water endowment, oceans cover about 70% of the Earth. For agricultural production it is freshwater that is of interest, although a small fraction of this comes from desalinisation [6]. Sources of water used for irrigation are:

- Primary and secondary surface water;
- Primary and secondary groundwater (renewable and non-renewable);
- Mixed primary and secondary surface water and groundwater;
- Directly used wastewater (treated or non-treated).

Desalinised water refers only to a few exceptional cases. According to estimates by [22], the annually renewable water in rivers and lakes is about 1% of average annual rainfall over continents. As a comparison, groundwater resources are about 250 times larger. However, slow recharge means that ground water is a stock resource while a continuous flux and variation in flow characterise surface water resources. Some two thirds of the planet freshwater are frozen in ice and snow caps.

The importance of groundwater as a strategic resource has grown. A major reason is that surface water is heavily exploited. About 1.4 billion people live in closed basins where additional allocations of water should not be expected. In addition, droughts and changes in rainfall pattern make the availability of surface water more uncertain. Conversely, access to cheap pumping technology, lack of enforceable regulation and, in some places, subsidised energy are important drivers in the contemporary exploitation of ground water. On average, groundwater is the source for a third of the world irrigation water with 70% of this being abstracted in Asia [23]. In the developing world, there is a striking difference between the contemporary boom in water exploitation and previous water development. Previously, projects were driven by state entrepreneurs, largely financed from public budgets and generally large scale, with magnificent landmarks that continue to attract attention. Today, while the number of pumps installed can be counted in the millions, they are typically small scale and small devices can be moved readily from one well and one site to another. Although there are no physical land-marks, they are significant in their imprint on water.

Arrangements for lifting and diverting water are observed in all parts of the world. In Africa, irrigation development has been much slower. Slightly less than 5% of the cultivated area is irrigated [10]. So far, most of the water withdrawn is through simple technologies and often by hand [24]. A thriving development of small private irrigation systems is facilitated through access to cheap Chinese-made motorised pumps [24]. For Sub-Saharan Africa, it has been estimated that the amount of water available as groundwater may be 20 times more than that available in the lakes and rivers [25].

2.2. Water needs of agricultural products

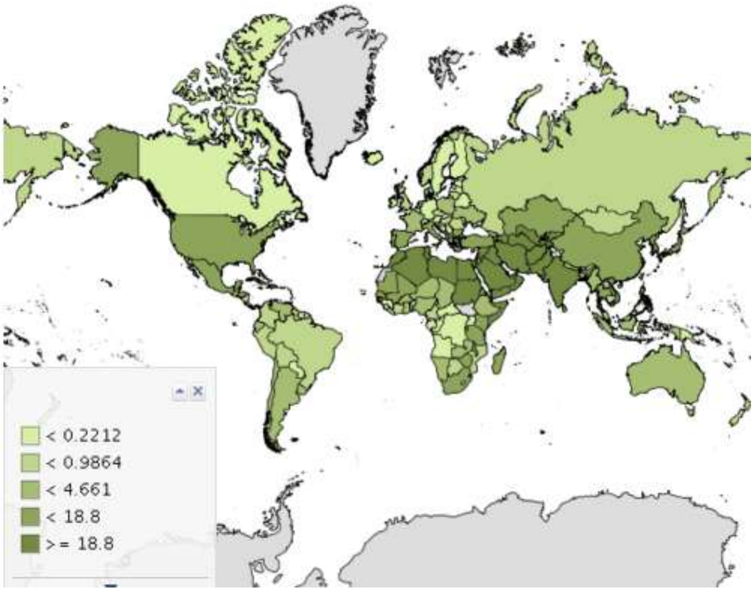


Figure 6 Water withdrawals, % intended to agriculture

The figure above shows how much water is used by country in agriculture and clearly underlines differences between different geographies. To estimate the pressure of irrigation on the water use and water withdrawal on the available water resources, an assessment has to be made both of irrigation water requirement and of irrigation water withdrawals.

Irrigation water requirement depends on the crop water requirement and the natural water contribution available to the crop, i.e. soil moisture, precipitation etc. On the contrary, irrigation water withdrawal largely exceeds irrigation water requirement due to significant losses in distribution and application.

In 2011, however, over 346 million ha of irrigated crops were harvested from the 261 million ha actually irrigated. Indeed, thanks to irrigation and if climate is favourable more than one crop cycle is permitted each year on the same area, resulting in a global cropping intensity for irrigated crops of over 130% [26]. The climatic conditions allowing various cropping cycles in a year in large parts of Asia, Africa and Americas, make a significantly larger cropping intensity in these regions than in other parts of Europe and Oceania, where irrigated crop growth in the winter season is little or non-existent.

The greatest potential for expanding irrigated agriculture, considering both land and water resources, is in the Sub-Saharan Africa region, where only one fifth of the irrigation potential has been equipped, or

7.7 million ha out of a potential of 38 million ha; and in the Southern America region, where only one fourth of the potential has been equipped, or 16 million ha out of a potential of 60 million ha.

The world's water requirement ratio, sometimes also named irrigation efficiency—that is the amount of water required for irrigated crops over the volume withdrawn for irrigation—is around 56 percent, depending essentially on geophysical characteristics. In addition to geographical disparity, the ratio also depends on financial resources availability. It increases from 48% in low-income countries to 56% in middle-income countries and 61% in high income countries.

Currently, overexploitation of groundwater - when water withdrawal exceeds water recharge and its subsequent lowering of water tables—is a recurring problem in the Arabian Peninsula and the Near East. It also often leads to seawater intrusion in coastal areas, drastically deteriorating the quality of groundwater. The drying up of the Aral Sea in Central Asia is one of the most dramatic examples of environmental tragedy caused by the mismanagement of irrigation: the sea level dropped by 17 meters and the shoreline moved 70 km since 1960s. This is due to the large diversions of water for irrigation of cotton and electricity production, resulting in little water reaching the Aral Sea [26].

Actually, there are different methods to evaluate water needs of agricultural products. The simplest one is to use tabulated data, but it could be far distant from crops real needs. The tabled needs identification is statistically reliable only for similar soil conditions and similar crops, affected by similar climate conditions, but if tabled data are used, nothing is site specific. Other more accurate methods are computer simulations, using software tools that use local data to calculate the specific water needs of a particular crop in a precise environment. For instance, CROPWAT, a computer program able to calculate crop water requirements using local data, developed by FAO [27]; WOFOST (WOrld FOod STudies) is a simulation model for the quantitative analysis of the growth and production of annual field crops, elaborated by the Centre for World Food Studies and Wageningen Agricultural University [28]. In Chapter 3, the CROPWAT simulation tool is described in detail.

2.3. Irrigation techniques applied

Water needs used by crops are lower than water withdrawals for irrigation, hence losses or inefficiencies occur during the collecting and distribution steps.

Irrigation is the artificial application of water to land or soil in order to assist crop growing process. In drought condition, irrigation will help to overcome shortages in precipitation and crop production can be substantially increased as the result of stable access to water.

Worldwide, in 2012 over 324 million hectares are equipped for irrigation, of which about 85% or 275 million ha are actually irrigated. Irrigated agriculture represents 20% of the total cultivated land, but it contributes 40% of the total food produced worldwide. Sub-Saharan Africa is the region with the lowest portion of the cultivated area that is irrigated, just over 3% against almost 21% at global level. At the same time it has the highest prevalence of undernourishment, 25% in 2011-2013 against 12% at global level.

In the following paragraphs, conveyance systems and irrigation technologies will be listed and analysed, in order to clarify the effectiveness of all the possibilities, according to [29].

2.3.1. Conveyance systems

Water conveyance from intake to crops is an essential element of the irrigation system, in most cases done via a simple earthen gravity canal in rural areas in developing countries. Water losses in such a system can be considerable due to evaporation and seepage through the canal bottom, particularly in sandy soils, which are the most permeable soils. Moreover, if water regulating structures are absent or inadequate, water distribution will be uncontrolled, leading to possible canal breakages and additional water losses. Open gravity systems have usually an efficiency of about 40%, very low considering problems of water scarcity or problems of energy access. Providing farmers with an irrigation pump but no further technical advice on how to distribute water to the fields and crops, has a high probability to cause large water losses and poor performance. It is therefore important in any irrigation system to pay adequate attention to the layout and design of the canal system in order to determine which system should be used, where improvements should be made and which regulating structures should be included. Pipe distribution systems are very efficient, with an efficiency of 90%, but require greater investment and more energy. Nevertheless, design and installation of both systems require adequate technical advice and support to be tailored to the specific situation.

- Open gravity canal system

In an open canal system (FIGURE 8), water is taken in through a diversion structure from a surface resource or from pumps. For larger areas where water has to run over several kilometres, a network of secondary and tertiary canals is required. These canals require proper layout and design, taking into account regulating structures to control water flow and levels in the canals and the distribution of the appropriate quantity of water to each canal segment, field channel and field outlet. To reduce water losses in the canal and to prevent erosion, particularly in sandy and unstable soils, canal lining should be considered for at least part of the canal system. Canal regulating structures include flow and water level regulators, drop structures, inlet and outlet points, as well as bridges and siphons for road and drain crossings. Given these technical requirements, adequate technical support is required to ensure the proper design and installation of an irrigation canal system, even for small irrigated areas of less than one hectare. Besides the layout and construction of the canal system, farmers need to receive training about operation and maintenance of the system in order to keep it away from not expected degradation and deterioration. Construction of a canal system involves excavation work for the secondary and tertiary irrigation and drainage canals as well as the flow-regulating structures. During the operational period, furthermore, it is necessary constant maintenance to prevent canals damages or to remedy in case of water overflow. In addition, part of the earthen canal system may need to be lined in order to reduce losses and convey water over difficult canal stretches. The costs include excavation work for canals, secondary and tertiary, costs relative to the possibility to line part of the canals and little regulation systems. The most commonly used canal cross-section in irrigation and drainage is the trapezoidal cross-section.

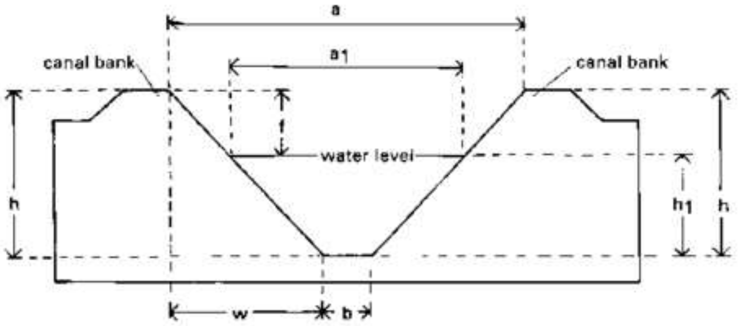


FIGURE 7 CANAL CROSS-SECTION

The freeboard (f in Figure 7) of the canal is the height of the bank above the highest water level anticipated. It is required to guard against overtopping by waves or unexpected rises in the water level.
a = top width of the canal
a1 = top width of the water level
h = height of the canal
h1= height or depth of the water in the canal
b = bottom width of the canal
f = h-h1
The bottom slope of the canal does not appear on the drawing of the cross-section but on the longitudinal section and it is linked to water velocity, it is given by the equation:

$$bottom\ slope(\%) = \frac{height\ difference\ (m)}{korizontal\ distance\ (m)} \cdot 100$$

- Low–pressure pipe system

The low-pressure pipe distribution system (*système Californien*) has proved to be an effective and efficient irrigation technology for small-scale farmers and small farmers' groups for conveying water efficiently to fields and crops [29]. The study refers to the review of the project Special Programme for Food Security, in which successes and failures of many irrigation techniques introduced over a period of more than 15 years, mainly in Africa, are examined. In general, for low-pressure pipe systems, most materials (PVC or Polyethylene (PEP) pipes, flexible hoses) are locally available and farmers can install the system with minimal technical assistance, or with help from locally trained private irrigation technicians. Used in combination with a small motorised pump, a pressure treadle pump, or used in a gravity system where water flows from an elevated small reservoir, the pipe system is able to efficiently convey and distribute water directly to the irrigated areas, rotating irrigation between the different pipe outlets. Pipe outlets or hydrants are placed at a regular distance (±20 m) on a fixed underground PVC system. The outlets can be opened directly to the field or connected to a flexible hose that can be dragged around to irrigate individual fields and crops. Low pressure pipe systems have been successfully introduced in several African countries, mostly with assistance from technical agencies. The investment required for low-pressure pipe systems is still high at around US$1000 to 1500/ha, but can easily be recovered as water allocation and easy operation ensure more accurate and efficient water application, resulting in higher yields, water savings and larger irrigated areas. Human involvement in feeding plants is not particularly high, but still necessary due to manual handling of flexible hoses, but expertise is not required.

FIGURE 8 EARTHEN CANAL

FIGURE 9 LINED CANAL

FIGURE 10 LOW-PRESSURE CANAL PIPE

2.3.2. Irrigation systems

- Sprinkler irrigation systems

Sprinkler irrigation has been widely introduced into communities and in individual schemes for both small and large areas. The technique includes a complete irrigation system with pump, distribution pipes and mobile laterals on which the sprinklers are placed. The system has high water efficiency, is easy to install and the equipment is readily available on the market because it is a tested technology. However, it may require high investment costs, because of the single sprinkler price, as well as high fuel costs for the operation of the pressure pumps and, in the situation analysed, these are the main reasons why the implementation of the technology failed or has been abandoned. In sprinkler irrigation, a pump takes up water from a water source (river, lake, canal or well) and conveys the water under considerable pressure (2–3 bar) through a lateral pipe system, of quick-coupling light-weight tubes, which can be moved over the field to the crops. The sprinklers are fitted to the pipe system, and water is sprinkled down through spray heads onto the crops in circular patterns. Water losses are low (<30 percent) and the system can be moved easily. No field levelling is required and limited labour is required to move the mobile pipelines along the field and connect the hydrants to the underground main-lines. The system is used in a range of different sizes and designs and it could also be used by small-scale farmers. Because of the mobility of the equipment, sprinklers systems have been applied successfully as supplemental irrigation in locations where rainfall is irregular or inadequate, which may save or boost crop production during dry spells. Major constraints of the irrigation system are the considerable investment and operational costs. In particular, the high fuel costs and energy requirements of the pressurized system make it one of the most expensive options and it has often proved to be uneconomical for most of the food crops cultivated by small-scale farmers. Investment costs for the sprinkler system include a motorised pump with the capacity to provide sufficient pressure, as well as the quick-coupling laterals, with sprinkler risers and the pressurised pipe system.

FIGURE 11 SPRINKLER IRRIGATION

- Drip irrigation systems

In drip irrigation, water is applied directly along the crop rows through small drippers fitted on flexible polyethylene tubes. The system can be very efficient in terms of water usage, reaching up to 90 percent and it applies the water very accurately to the crop, which results in optimal crop yields. Drip irrigation is applied successfully in most high-level commercial fruit and vegetable farms and greenhouses. Family drip irrigation and bucket drip irrigation systems have been commercially developed and introduced in southern Africa specifically for small-scale farmers. A 10 – 15 L bucket reservoir or 200 – 300 L fuel tank is placed at an elevated height (1 or 2m) above the field and is connected to the small tubes and drippers to irrigate a small vegetable garden area of usually 50 m^2 in the case of a bucket reservoir or 250–500 m^2 in the case of a drip irrigation with a larger reservoir. Although an effective technology, drip irrigation systems for small-scale farmers have failed in several cases, as farmers have not been adequately familiarised with the operational aspects of the technology. Difficulties including the frequent filling of the bucket or reservoir; access to the water source; unfamiliarity with the frequency of water application; water not clean enough or with sediments; and failure to clean the filter system regularly, have been the cause of disappointing performance and failure of small-scale drip systems. The investment for a bucket or family drip irrigation system is considerable. Even though the costs of a bucket drip unit (US$50) and family drip unit (US$300) are relatively modest, the investment costs per hectare could be remarkable, as the area covered by a single system is quite small (50–250 m^2). Also the labour costs to refill the bucket and water tank regularly are significant.

FIGURE 12 BUCKET DRIP IRRIGATION

- Small-scale and community irrigation systems

Small-scale and community irrigation systems have been widely introduced in southern Africa to promote irrigated agriculture for small-scale farmers. Systems may vary in size from 5 to 200 hectares and may include river diversion, small dams or pump schemes. Results have not always been positive due to lack of ownership and inadequate involvement of the community in planning. Operation and maintenance have proved a major challenge and operational costs were often too high for the cultivation of food crops by small-scale farmers. Three basic types of small-scale or community irrigation schemes can be distinguished, depending on how water resources are mobilised for irrigation, namely river and spring diversion schemes, pump schemes and small dam schemes.

- Efficiencies

Not all water reaches the root zone of the plants, some is lost during the transport and some is lost due to water losses in the field. The first water losses, namely *losses in canals*, are due to [30]:

- Evaporation from the water surface
- Deep percolation to soil layers underneath the canals
- Seepage through the bunds of the canals
- Overtopping the bunds
- Bunds breaks
- Runoff in the drain
- Rat holes in the canal bunds

About water *losses in the field*, they can be divided as follows:

- Surface runoff, whereby water ends up in the drain
- Deep percolation to soil layers below the root zone

To express which percentage of irrigation water is used by plants and which one is lost, the term *irrigation efficiency* is used. It is divided in two other terms, the *conveyance efficiency* (ec) and the *field application efficiency* (ea). The conveyance efficiency represents the efficiency of water transport in canals, the other one refers to the water application in the field. Ec mainly depends on the length of the canals, the soil type or permeability of the canal banks and the general conditions of the canals. Table 2 provides some indicative values of the conveyance efficiency considering the length and the soil type [31].

Ec values	**Earthen canals**			**Lined canals**
Canal length	Sandy soil	Loamy soil	Clay soil	
Long (>2000m)	60%	70%	80%	95%
Medium (200-2000m)	70%	75%	85%	95%
Short (<200m)	80%	85%	90%	95%

TABLE 2 INDICATIVE VALUES OF THE FIELD APPLICATION EFFICIENCY (EA)

The field application efficiency depends on the irrigation method and the level of maintenance of the system.

Irrigation methods	**Field application efficiency**
Surface irrigation (border, furrow, basin)	60%
Sprinkler irrigation	75%
Drip irrigation	90%

TABLE 3 CONVEYANCE EFFICIENCY EARTHEN AND LINED CANALS

The scheme irrigation efficiency is calculated through the formula:

$$\eta = ec \cdot ea$$

2.3.3. Pumping systems

The way to pump and distribute water is another variable parameter. A range of technologies have proved their effectiveness for different conditions related to climate, soil and available water resources. Selection of the appropriate technology according to the given agro-ecological context is a key to success or failure. To have an overall view of the advantages of different solution and to compare them, they are presented in terms of technical requirements, design concepts and common constraints.

- Treadle pumps

Originally developed in Asia, the treadle pump has been extensively introduced in many African countries, and this easy type of pump is promoted by several international agencies and specialised NGOs to show its potential. This micro-irrigation technique, which requires a relatively modest investment of around US$100, allows the small-scale farmer to irrigate a more substantial area than is possible with the traditional watering can method. Lifting water from up to a maximum depth of 7m, the use of the treadle pump permits a typical area of 2000 to 3000m^2 to be irrigated with at least four hours daily pumping for an output of around 1L per second. Treadle pump technology has been evaluated substantially since its first introduction in the 1970s, and a range of models has been developed by various organisations, including the FAO, using different materials and improving design and manufacturing. Two main types can be distinguished by the way the outlet operates: the *pressure* treadle pump and the *gravity* treadle pump. The pressure pump has proved more successful, as it can be connected to a flexible hose that allows direct watering of the crop.

The spread of the technology inside the Special Programme for Food Security was facilitated by promoting local manufacturers, often through separately financed projects and with the assistance of specialised international NGOs. Yet the initial enthusiasm for the treadle pump has been tempered, as the technology showed a number of setbacks and limitations in several programs [29], and proved less sustainable for a number of reasons. These constraints included:

- Poor quality of local manufacturing and frequent breakdowns;
- Inadequate technical advice for installation and operation of the equipment;
- Considerable daily labour required to pump water;
- Limitations, in particular of the gravity model, as the small volume of water cannot be transported over any distance to the crop;
- The high position needed for operating the treadle pump, in particular in the early models, causing discomfort to women;
- Sharing of the treadle pump among a group of users proved less successful.
- The treadle pump has been more successful in wetland development projects where groundwater can be found at a shallow depth (<3m). When combined with well development, the pressure treadle pump can be connected via a set of low-pressure pipe distribution system and flexible hoses to distribute the water by sprinkling. The investment for the pressure treadle pump, including a set of flexible hoses for intake and output, is around US$120 per treadle set irrigating 2500m2, which means around US$500/ha. Labour costs to operate the treadle per season are high because of the necessity of work force specifically addressed.

- Motorised pumps

Motorised pumping has revolutioned irrigated agriculture and made an important contribution to securing food production and income for small-scale farmers in many countries. These small low-cost motorised pumps are an attractive and successful technology suitable for an individual farmer or a group of small-scale farmers. Individual farmers may extend their garden plots to irrigate a larger area as a result of the motorised pump, while groups of farmers can irrigate a common or collective area. Equipment has proved reliable provided that adequate maintenance is undertaken and spare parts are available. These assumptions have to be further explored in loco. However, fuel costs and access to fuel constitute a big constraint for small-scale farmers. Larger pumps often pose management problems, as the larger irrigated areas require good conveyance and distribution systems, preferably with lined canals or low-pressure Polyvinylchloride (PVC) pipe and flexible hose outlets for smaller pump systems. In many cases, small-scale and village irrigation schemes could be equipped with motorised pumps for areas of 5 to 200 ha, but organizing farmers into water users associations (WUA) to ensure adequate operation and maintenance (O&M) could be difficult. Inside the Special Programme for Food Security there are many examples of pump schemes that have failed due to poor cooperation among farmers. The small low-lift motorised pumps driven by small petrol or diesel engines with a capacity of 2 to 5 horsepower (hp) and a typical discharge of 2 to 5L/second have proved cost-effective. The price of this centrifugal pump has substantially decreased as the result of imports from China and India, and is typically between US$200 and US$500. As a result, more established small-scale farmers can afford this technology and it allows them to irrigate a substantial area of 1 to 5 ha. The operational costs are mainly fuel costs, which have to be estimated locally.

- Solar pumps

Solar pumps allow users to avoid the constraint of the high fuel costs for motorised pumps. The electric pumps linked to the solar energy units have proved reliable and have low maintenance costs. Energy outputs of solar panels are limited, however, and in most cases a solar-driven electric pump may irrigate smaller areas, depending on solar source and available space. The solar pump unit includes solar panels, a battery pack with current regulator unit for energy storage, and an electric motor linked to the water pump. To irrigate effectively, water needs to be stored in a water reservoir or tank and connected to a pipe system or drip system. Initial investment is very high and often difficult to justify economically. There are extra components that mean extra costs to be taken into account if connected to either a pipe system or drip irrigation system, which are most suitable for efficiently conveying the low pump discharges to the crop. However, operational and maintenance costs for a solar system are relatively low because no work force is required; therefore it may be worthwhile for farmers to consider the long-term investment benefits of using solar energy to pump irrigation.

FIGURE 13 TREADLE PUMP, MOTORISED PUMP, SOLAR PUMP

2.3.4. Wells

- Shallow wells

Groundwater has proved a reliable and accessible water source for irrigation. Several low-cost technologies have been developed including open well lining and shallow tube wells to improve access to groundwater for irrigation or drinking water. Water depth and variability in depth and quantity can be constraints as the common pump systems do not allow water to be pumped from a depth of more than seven meters. Capacity building to train local drilling teams and provision of technical advice on suitable sites and procedures need to be ensured. Some international NGOs in southern Africa are now successfully engaged in the promotion of shallow well technologies and capacity building of local craftsmen, such as Practical Action in Turkana [32].

- Open wells

Traditionally, farmers have developed open wells, up to 15–20 m in depth, for drinking water and for garden irrigation using buckets. Open well development is most common, particularly in the bottoms of valleys and wetlands where groundwater is at a shallow depth and farmers dig open pits for bucket irrigation. Because in unstable and sandy soils shallow pits collapse easily, well construction techniques have been improved: the pits are lined with concrete rings, bricks or stone masonry, allowing groundwater to be sourced from greater depths. The costs for open wells can vary considerably depending on the well's depth and the equipment required for drilling. Traditionally, open well digging carried out by local craftsmen (with or without brick lining) is a cost-effective option.

- Shallow tube wells

Shallow tube well drilling is a relatively new and promising technique for southern Africa that has proved particularly effective with PVC tubing, which is now widely available, even in rural areas. Several new and cost-effective techniques for tube well drilling have been developed for different hydro-geological conditions, which allow drilling in various soil conditions, such as sand and hard stone layers. Shallow well development techniques include:

- Augering of tube wells
- Sludge drilling for tube wells
- Percussion drilling
- Jet wash boring
- Stone hammer drilling
- Rotary rigs.

Specialised international NGOs have played an important role in the introduction of shallow tube wells and in training local entrepreneurs in new well development techniques, such as the rota sludge technology. Through the training of local drillers, the technologies can be made available for farmers at affordable costs. Deep tube wells beyond 30 m require specialised drilling equipment and multiple stage pumps, thus the price of such a deep well pump can be greater.

2.4. Local energy resources and possible exploitation technologies

Decentralised diesel generators are a major source of power supply in Asia, Africa and island communities, where many areas either lack access to the power grid or suffer from frequent blackouts due to poor energy infrastructure. Additionally, industrial sectors such as telecommunication and Oil & Gas in developing countries have operations in regions not connected by the grid and thus deploy a large number of stationary diesel generators to supply power. Diesel exhausts from these stationary generators contain Nitrogen Oxides (NO_x), Carbon Monoxide (CO), Carbon Dioxide (CO_2), carcinogens and particulate matter that are major source of air pollution. Besides air pollution, communities dependent on diesel generators are exposed to diesel price volatility and high operational and transportation costs [33].

Alternative solutions to decentralised diesel generation that have been implemented with success in the past include solar-PV hybrid plants, bio-gasifiers, solar-wind hybrid systems and community micro-hydro plants. Historically, reasons for limited penetration of these cleaner alternatives have included relatively high cost of renewable energy technologies, additional storage requirements and funding gaps in developing nations.

Locally available renewable energy exploitation could be a sustainable way to produce the energy required by irrigation systems. Without the previous study on water needs and constraints, energy system is separated by the water system. This could represent a problem of oversized or undersized irrigation configuration, from both the energy and the water distribution point of view. Very often in developing countries information about energy consumption are collected through surveys and they are not checked. Nevertheless, once the energy load curve is estimated, the energy system could be elaborated and simulated to evaluate its performance.

In the following paragraphs, the necessary assumptions to elaborate an energy system are explained, while in Chapter 3 the available simulation tools are presented.

2.4.1. Energy sources

Power systems

At the beginning of the electrification era, systems were decentralised while at the end, systems moved to centralised electrical plants in order to minimise investment costs. There were built large power plants in central location to reduce drastically power losses in transportation and distribution grids, and to serve a huge number of consumers. In '80s, two main drivers made it possible to shift the previous paradigm of complete monopoly exercised by state owned companies:

- Increased efficiency
- Attraction of private capitals

In developing countries, there are constraints that should be overcome to take a step through the evolution process. First of all, the little autonomy of monopoly enterprises in relation to governments, the poor financial capacity, the aid capital allocation that is seldom dedicated to capital investment and too often to maintenance; finally the focus on the urban areas that totally hides rural needs because of the lower economic interest.

Otherwise, the power system classification includes the centralised systems and the off-grid power systems. The second group could be further divided in decentralised and distributed systems. In order to analyse each strategical approach, advantages and disadvantages should be taken into consideration. In centralised systems, through their large dimension in terms of nominal power and regarding the great transmission and distribution grids, the main positive factor is the *size effect,* meaning the reduction of costs linked with the increase in plant size. The more users are involved, the lesser is the cost per unit output. It is not an endless correlation, the cost curve presents a minimum value in correspondence of a certain value of users, behind which total costs start to increase again because of the greater weight of the grid enlargement cost in contraposition to the revenues deriving from more users.

Decentralised systems means a specific kind of power generation, based on one single source and addressed to a little number of users, often it is a stand-alone system. This solution is locally based and deeply need oriented.

The last off-grid power system is the *distributed system*, which is a set of decentralised systems, interacting through a transmission and a distribution grid, so that they can serve a greater number of users.

The shift from centralised generation to off-grid plants is pushed by some remarkable factors during the last decades. Firstly, the technological improvement that concerns the small power production made it possible to overcame the technical constraints. The control equipment and electronic metering are more and more accessible and developed. On the other hand, also the demand has changed during the years: consumers expect highly reliable power supply, both in terms of constancy of the furniture and in effective power request. Those noticeable enhancements in small power technologies, which are for a large part based on renewable sources, are moved by environmental purposes, aiming to reduce greenhouse gas emissions worldwide. Nowadays, public awareness of electric production industry and its impact on the environment address and influence the efforts in technological innovation. The advantages are not only in environmental dimension, but also in the economic sphere. Avoiding centralised generation means not to pay the transmission and distribution grid costs related to this strategical choice. What is more, the risky nature of large scale plant investments is put aside when selecting off-grid systems. There are lots of variables that could be evaluated in order to maximise the competitive economic advantage of decentralised power production, for example combined heat and power generation. Governments, through incentives that make the off-grid solution cost effective, play again a central role. Another important point is the political independency that decentralised and distributed generation based on renewable energies could ensure. Without fossil fuel necessity, countries could increase the diversification in their *energy mix* in order to reduce their vulnerability. At last, promoting green technologies means exactly to fulfil a public growing desire, letting the sustainability of the intent be remarked and carried out.

The decentralised and distributed systems in DCs are often based on renewable energies locally available, not excluding diesel generation. These systems are designed for rural areas, which means a particular target population, usually scattered and isolated, presenting high difficulty to access. This factor is relevant when considering the installation phase of an energy system, for instance transporting a wind turbine, even a micro one, could be not feasible if there are no paved roads. At the same time, for these places extending the national grid is not an alternative because of the high investment costs due to transmission and distribution expenses. Another important issue is the very low economic activity of these areas, which means the investments suffer the risk of non-payment by population. The systems, for the reasons explained, are usually small in terms of peak power, ranging from a few kW to 5MW. The innovative aspect is the focus on local needs, instead of a large-scale production independent from the single demand.

The major difference between decentralised and distributed systems is the number of sources exploited: in the first case, only one source is used to supply home based systems, or community based systems or even small/medium enterprises based systems; in distributed systems, there is a multi-source and a multi-component scheme and generally it supplies energy to a wide range of users. In distributed solutions, it is often used a traditional source - diesel generators are very common- and it is called *hybrid system.*

In order to analyse in detail every possible configuration, for small-scale off-grid power systems, there are three possibilities:

- Conventional
- Non-conventional
- Hybrid

The conventional technologies are mainly diesel-powered generators named also gen-sets. Gen-sets are dispatchable depending on demand side, even for low rural power curve. The solution is cheap considering the initial investment cost and it does not require civil work for installation. The range of diesel generators goes from 3kW to high power, depending on the load they have to satisfy. On the contrary, the maintenance and operational costs are the highest, due to fuel price and fuel transportation costs that could be unpredictable. During the daily operations, diesel generators should work at the maximum load to obtain the higher efficiencies, but it is not ensured that they operate in this optimum state. It often happens that the load is about 20-30% of the nominal conditions, with strong decrease on overall efficiency. This causes a negative impact on the environment, because the emission rate increases when operating far from nominal conditions, on the assumption of the same amount of energy produced. In cities, the noise generated should not be underestimated.

Non-conventional systems refer to renewable energy technologies (RETs), such as photovoltaic, wind, micro-hydro systems. The major positive factor of these solutions is the energy security they ensure. On the long run, RETs allow to reduce energy prices, because efficiencies are increasing while costs are decreasing. The solutions are flexible and it is possible to set modular systems with very low maintenance costs and environmental impact. As an example of their low impact on the environment, the energy payback time of a solar panel is around three years in Europe [34].

Those solutions have to face their intrinsic unreliability, essentially due to unpredictable weather conditions. To enhance their continuity in production, it is very often added a storage system to the configurations, which increase notably the costs that are the higher in terms of initial investment. The aleatory nature of the renewable sources, in particular solar and wind, makes it unavoidable in order to ensure a higher level of autonomy to the energy supply. In small scale off-grid power systems, non-conventional systems in theory include biomass-based technologies, but in reality they are few applications. This is mainly due to minimum plant size considerations: for electricity production, it is around 10-100kW, matching the micro-grid scale, but not the home-based nor the community-based typical size. Furthermore, the supply chain is much more complex than the other RETs. In developing countries, the traditional biomass consumption is already a disputed problem and a massive use of this source results in health and environmental issues.

Typical efficiencies, sizes, LCOE[1] (described in following paragraph), emissions of renewable sources are resumed in Table 4 [35].

	Efficiency %	Minimum size W	LCOE \$/kWh	Emissions gco2eq/kWh
SPV	15-18	1-1O	0.26-0.75	23-45
Wind	35	Hundreds	0.15-0.40	4.6-55.4
Hydro	90	Thousands	0.01-0.40	0.3-13[2]/4.2-152[3]
Biomass	10-20	7000-8000	0.08-0.14	63-70

TABLE 4 RETS PARAMETERS

The last option is a trade-off between the alternatives analysed and it is a *hybrid system*. The typical layout is a diesel generator and one or more RETs depending on the needs the system is designed to meet. The reliability and continuity of supply is strongly enhanced, together with the reduction of the storage system size. The investment and maintenance costs are higher due to the diversity of the components and fundamental is the ability required because of the presence of different technologies. The users should manage in the correct manner a plurality of technical components.

With the terms "hybrid system" could be named also a solar photovoltaic system coupled with a small hydro, or wind coupled with small hydro, the fact is that a hybrid system could be made of two renewable sources.

A typical dispatch strategy in presence of more than one aleatory source, for instance PV and wind, is to:

1. Store the excess electricity from wind turbine and PV, when the demand is lower than wind turbine production;
2. Cover the excess load through PV production when load demand is greater than wind turbine production;
3. If not all the peak load is covered by instantaneous production, additional energy is taken from the storage (a detailed description of a storage system is reported in paragraph 2.4.3).

It is clear that in these configurations there are mandatory components, like a converter for the PV array or the battery bank and an AC/AC converter for the wind turbine. Furthermore, there must be an AC bus line and a DC bus line. It depends on the DC loads and AC loads to meet, on the choice of direct or indirect coupling, on the presence of batteries. The connection scheme could be mixed bus line, as shown in Figure 14 and in Figure 15.

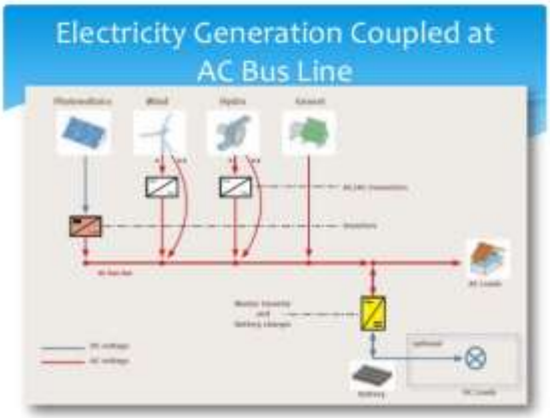


FIGURE 14 AC BUS LINE

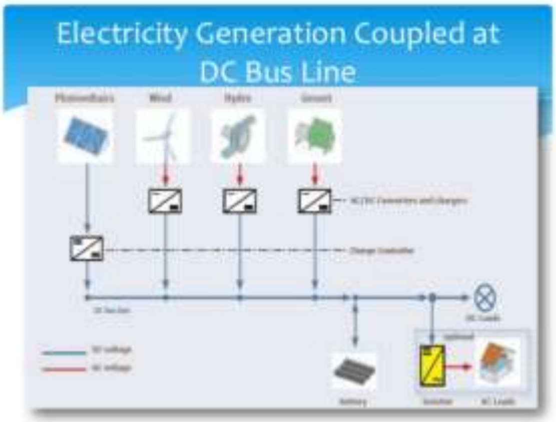


FIGURE 15 DC BUS LINE

Next section is about physic principles and functional parameters that affect each renewable resource.

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[1] Levelised Cost Of Energy

[2] Run-of-river small hydro

[3] Small hydro with basin or dam

To have an idea of the huge solar energy theoretically available on Earth, suffice it to consider the solar energy that arrives on a square meter, called solar constant, equal to $1350\,\frac{W}{m^2}$. Hence, the energy intercepted by the entire Earth is $1.75 \cdot 10^{17} W$, while the total power the Sun irradiates in space is about two billion times the power intercepted by Earth. Not all the energy arriving to Earth reaches the Earth surface and not all the energy could be collected and used. The solar radiation is geographically distributed as in Figure 16. If the inlet power is $1.75 \cdot 10^{17} W$, a great portion is lost by reflection ($0.525 \cdot 10^{17} W$,) so only a power of $1.225 \cdot 10^{17} W$, reaches our surface. In unit surface, it is equal to $1\,\frac{kW}{m^2}$. This energy is converted in:

- Heat $0.817 \cdot 10^{17} W$;
- Evaporation, rainfall, snow etc. $0.404 \cdot 10^{17} W$;
- Marine currents, wind and waves, photosynthesis on Earth and in oceans $0.004 \cdot 10^{17} W$.

The energy coming from gravitational energy that causes tides should be added and it is equal to $3 \cdot 10^{12} W$. Clearly, the energy arriving on Earth is not captured, otherwise temperature would reach unsustainable values.

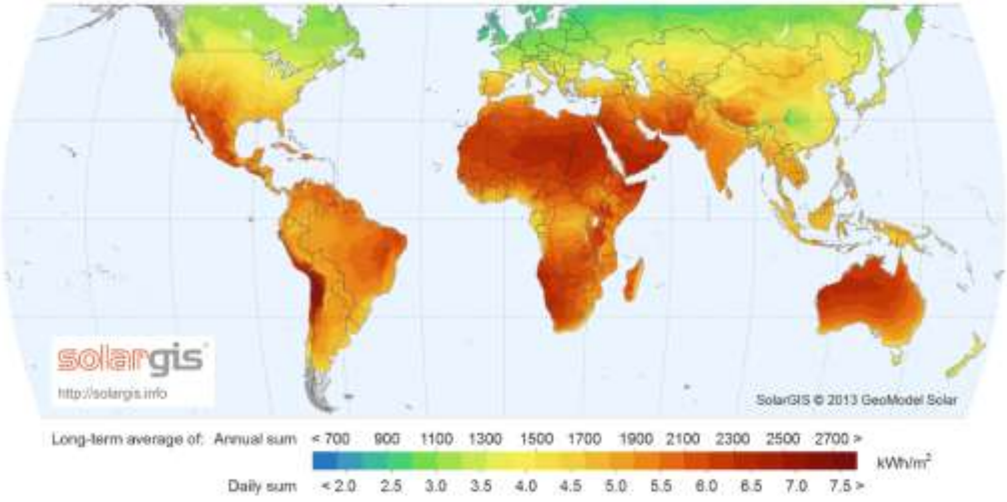


FIGURE 16 DISTRIBUTION OF SOLAR HORIZONTAL IRRADIATION

- Solar energy

Solar radiation reaching Earth could be collected through photovoltaic panels, with a direct production of electricity. Photovoltaic plants could be fixed or with tracking and in tracking systems there is a further sub classification, which depends on the presence of concentration mirrors (named Without Concentration and Concentrated Solar Plants). In this sub-section, the focus is upon simple plane non concentrated fixed photovoltaic panel and the physical principles that make possible to exploit solar energy.

A photovoltaic panel works with the photoelectric effect, discovered in 1839 by Becquerel. In a semiconductor such as silicon, thanks to thermal agitation that occurs at temperature other than thermodynamic zero, electrons gain energy to free themselves. When silicon is illuminated with light, on condition that photos have sufficiently high energy, many more electrons can move and the material act as a conductor. In particular, electrons move from a fully occupied band, the valence band, to an unoccupied band, conduction band, whenever they gain the required energy, which is called *energy gap* (or band gap). It is common to dope the semiconductor in order to improve its electrical transport properties and boron and phosphorus are mainly used. To practically generate electricity, it is required a device to separate the charges and to create an electromotive force that makes electrons flow in an external circuit. The device described is a diode. The current generated is

$$I = I_0\left[\exp\left(\frac{eV}{nkT}\right) - 1\right] - I_{\mathrm{L}}$$

Where I_0 is the inverse saturation current or dark current, I_{L} is the photogenerated current and n is an idealist factor to take account of defects in the diode. The electrical representation of a photovoltaic cell is shown in Figure 17.

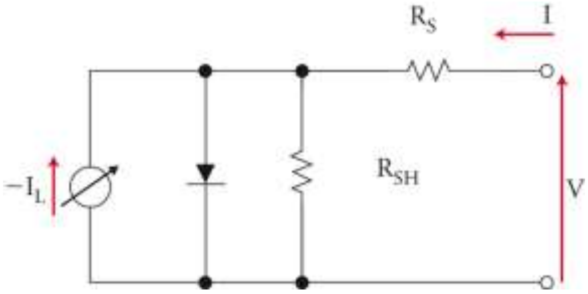


FIGURE 17 ELECTRICAL SCHEME OF A PV CELL

Losses typically are due to recombination of electrons, lack of light absorption, Joule losses, mismatch losses and optical losses due to glass and connectors.

Three points are important in the curve current-voltage, the Maximum Power Point (MPP), the short circuit current (I_{SC}) and the open circuit voltage (OC). I_{SC} is the maximum current at zero voltage, V_{OC} is the maximum voltage at zero current. MPP is the point individuated by a couple ($(\mathrm{V};\mathrm{I})$ that defines a rectangle whose area is the biggest (Figure 18).

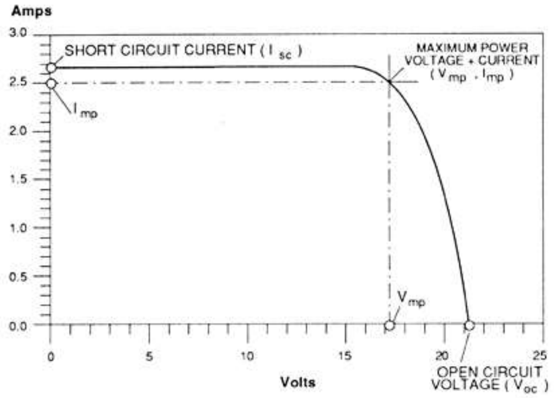


FIGURE 18 TYPICAL V-I CURVE AND POWER PRODUCED BY A PV CELL

There are different types of solar photovoltaic cells, the simplest ones are crystalline silicon or multi crystalline silicon. Other cells like amorphous silicon cells are used when solar radiation has an high percentage of diffuse radiation, or thin film solar cells used when architectural integration is require, as happens in high density urban areas.

To calculate peak power of a solar module, it is necessary to know its nominal efficiency η and the module surface. This information are available from producers, instead the effective energy production depends on local solar irradiance and Balance Of System (BOS) efficiency, which includes deviations due to temperature, mismatch losses, inverter efficiency.

$$P[kW] = S \cdot \eta \cdot h$$

Where h is the peak radiation intensity equal to $1\,\frac{kW}{m^2}$

- Wind energy

Wind energy is around 2% of the solar energy reaching Earth, thanks to the pressure gradient inside the atmosphere generated by solar radiation. Wind energy is diffused around the Earth, but only in few regions, it reaches valuable wind speeds that make it exploitable. The physical principle is the transformation of kinetic energy in mechanical energy through a machine, the wind turbine. A wind turbine has many components, its size could be very different depending on the specific application. However, main components are a hub, which generally is the support for three blades, a main bearing, the shaft, eventually a gearbox and a high-speed shaft, a brake and the generator. The turbine generates a power given by:

$$P = \rho \frac{v^3}{2} A c_p$$

Where c_p is the power coefficient and it depends on the air-machine interference. For an ideal turbine, $c_p \cong 59\%$, but for real turbines, $\eta_{II} = \frac{c_p}{c_{p,ideal}} \cong 80\%$. The wind turbine is an uplift machine, it uses variable geometry aerofoils to generate lift and drag forces. Lift force is created by the pressure difference between the two sides of each blame. Drag force is due to fluid resistance.

To decide to adopt a wind turbine, a wind speed assessment is required. Data collection should last at least one year to overcome seasonal variability in wind speed values, but it is preferable to collect data along years, usually three. Wind speed is collected at different heights, to calculate the *wind shear*, given by:

$$u = u_1 \left(\frac{z}{z_1}\right)^{\alpha}$$

Where u_1 is wind speed at the height z_1, α is the *wind shear exponent,* a parameter that depends on soil roughness and air stability. Having different speed values at different heights, it is possible to find α. With the average wind speed and information on gusts of wind, the possibility to install a wind turbine could be evaluated. The choice falls on the turbine whose nominal power is reached at the average wind speed of the location of interest.

In wind energy, the area swept by the wind turbine rotor is an important aspect because it determines the nominal power of the machine, it ranges from few meters, as an example, a micro turbine could use a rotor only 1.2m in diameter, to the 6MW wind turbine with 126m in diameter [36].

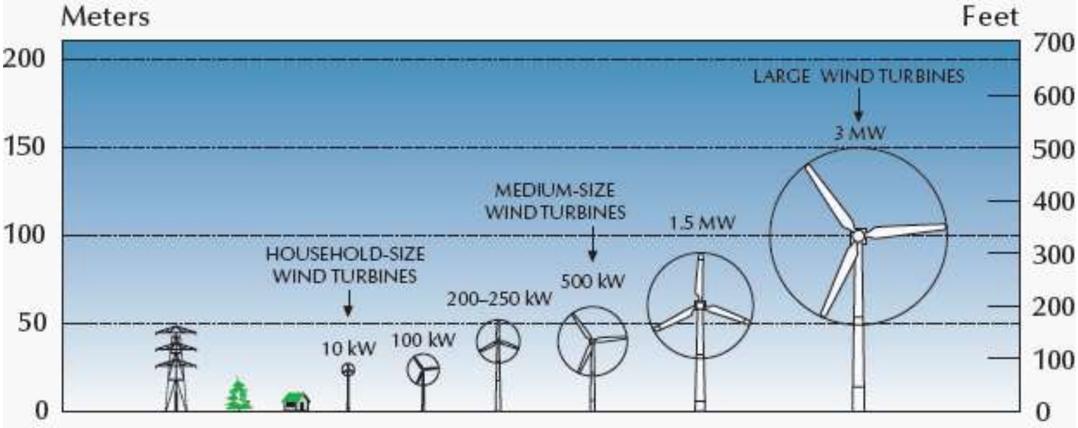


FIGURE 19 WIND TURBINE SIZE

	Rotor diameter	Swept area	Standard power rating
	m	m^2	kW
Micro	0.5÷1.25	0.2÷1.2	0.5
Mini	1.25÷3	1.2÷7.1	0.5÷60
Household	3÷10	7÷79	60÷100
Small commercial	10÷20	79÷314	100÷500
Medium commercial	20÷50	314÷1936	500÷1000
Large commercial	50÷100	1936÷7854	>1000

Table 5 Wind turbine size classes [37]

- Hydro Power

The hydro potential derives from precipitations, another form of indirect dollar energy. Basic concepts are flowrate $(\dot{m})$ and head(H):

$$E[J] = m \cdot \mathrm{g} \cdot \mathrm{H}$$
$$P[W] = \dot{m} \cdot \mathrm{g} \cdot \mathrm{H} \cdot \eta$$

Energy is produced by the transformation of the kinetic energy of the fluid inside a hydraulic turbine, where water arrives from a conveyance pipe or it is directly diverted from the river in case of a run-of-river configuration. The measurement campaign should be long enough to avoid seasonal variability problems about flowrate. Data about water resources could be obtained by online databases or through a direct evaluation, using for instance simple field methods, such as *velocity-area method* or *weir method*. To evaluate the waterfall, a GPS device could be evaluated.

Hydro power plants could be divided in different ways, for instance run-of-river and systems with small basin. They could be differentiated considering their head: high (>100m), medium (30÷100m) or low (2÷30m). Last classification is about size: big plants – power greater than 10MW; small plants – power from 1MW to 10MW; small hydro, in particular mini hydro – power from 100kW to 1000kW – and micro hydro – power lower than 100kW. Main components of a small hydropower system are the intake weir, channel, a forebay tank, penstock, turbine and generator.

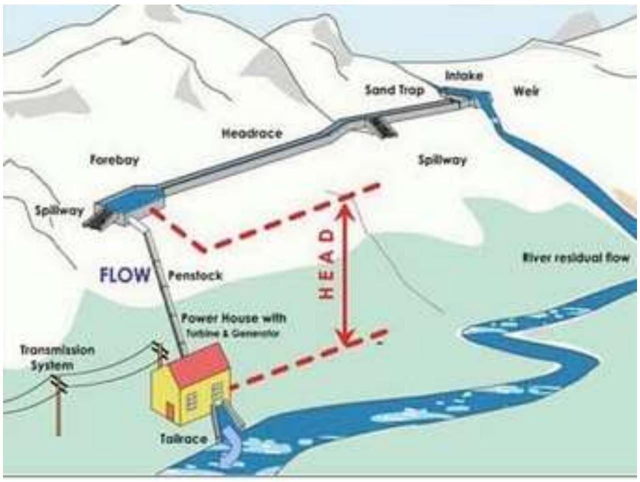


Figure 20 Micro hydro system

- Biomass energy

With the term *biomass* it is named both animal and vegetal residuals, but they are completely different. Vegetal biomass includes agricultural residuals, agro-food industry residues, forestry waste or energy crops

cultivation. On the other side, animal biomass includes slaughter waste, animal waste and again agro-food industry residues. Biomass could be classified considering its atomic structure, its physical chemical components (cellulose content, lignin…), or its volatility, which depends on humidity, ash and fixed carbon quantity.
From energy crops, it is possible to make different processes:

- Biologic conversion: it includes processes like fermentation and aerobic digestion, respectively to produce ethanol (directly used in transports) and biogas (used in gas turbines);
- Thermos-chemical conversion: the most common treatment is combustion, although it is possible to proceed the biomass through gasification, pyrolysis, and liquidation. All these processes have the purpose to generate electric energy, by a Rankine cycle (combustion) or through a gas turbine (gasification and pyrolysis);
- Oil extraction: the result of an oil extraction is a vegetal oil which is later processed through esterification, giving a bio diesel, used in transports.

Power production is calculated through the equation:

$$\mathrm{P[kW]} = \eta \cdot \dot{\mathrm{m}} \cdot \mathrm{LHV}$$

Where η is the plant efficiency, $\dot{m}$ is the biomass that enters the plant and LHV is the lower heating value of the specific biomass (fuel).

The management of a biomass plant is complex and it is usually not a valid option in rural areas, because of the high skills required and the minimum plant size that makes the investment feasible.
In the following section, drivers and barriers are explained for each renewable resources, in terms of technical but even social, economic and environmental aspects.

2.4.2. Technologies overview

As seen in Table 4, LCOE is often a comparison parameter for different technologies. The Levelised Cost of Energy is defined as the ratio between the total cost of supplying electricity plant and the plant lifetime considering the discount rate. Costs include construction, operating and maintenance, so even the fuel cost is a variable of interest.

$$GenCOST = CapCOST + OpCOST$$

$$CapCOST\left(\frac{\$}{kW}\right) = \frac{Equipment(eng) + Civil + Process\ Cost}{Generation\ Capacity\ (kW)}$$

$$Levelised\ Capital\ COST\left(\frac{\$}{kW}\right) = \frac{\sum_n \frac{C_n}{(1+r)^n}}{\sum_n \frac{E_n}{(1+r)^n}}$$

$C_n = capital\ cost\ in\ the\ nth\ year$
$n = life\ span$
$E_n = net\ electricity\ supplied\ in\ the\ nth\ year$
$r = discount\ rate$

$$OpCOST\left(\frac{\$}{kW}\right) = \frac{Fixed\ and\ Variable\ O\&M + Levelised\ Fuel\ Cost\left(\frac{\$}{year}\right)}{Net\ electricity\ \left(\frac{kWh}{year}\right)}$$

The operation and maintenance cost is made of operating labour, general and administrative cost; the variable includes maintenance labour and materials, suppliers and consumables; the Levelised Fuel Cost is calculated according to:

$$LFC\ Levelised\ Heat\ Unit\ Price\left(\frac{\$}{J}\right)\cdot Gross\ Heat\ Consuption\ \left(\frac{J}{kWh}\right)\cdot Gross\ Electricity\ \left(\frac{kWh}{year}\right)$$

RETs should be compared considering not only the LCOE or the cost of energy (COE), but also other important parameters. Indeed, considering the power request trend along the days and the seasons, the resource availability leads to different considerations. Solar PV is available only during daylight and it is variable according to the season; small wind resource is variable during a single day and during seasons; the same applies to hydro and eventually to biomass production due to seasonal crops yields. The first step is data collecting, but for some renewable sources, there could be historical data, like climatologic data, which are easily available. For micro-hydro, in most cases there are no data at all, the collection phase would take a long time because of the necessity to consider seasonal variations. These considerations are valid also for biomass resource. To identify the optimum solution the possibility to install the system close to the energy utilization should be evaluated, which could be impractical in wind application due to pale size and even noise problems. Furthermore, every site has its own physical restrictions, like available space: in solar applications, the ratio surface-power is high, in wind small size plants, space for setting up includes the space required to lay down the turbine for maintenance. In PV systems, the placement of the array has to avoid shadowing problems; in wind applications, the site should not present obstacles in order to leave the wind profile unaffected. In developing countries, there could be constraints also in the civil engineering level, so choosing a RET should be influenced by the practical feasibility of the system. PV configurations require low civil works, but wind systems need medium to high civil works, depending on the ground and the soil. For micro hydro civil works are usually high regardless the turbine size. For what concerns the needed operation skills they are low for all RETs except for maintenance, which required specific competences for every technology chosen. It would be interesting to evaluate the level of implementation of the existing systems around the area of interest. Very often renewable energy technologies need batteries storage in order to minimize their aleatory production and to fit better their production to the demand. In hydro and biomass systems, the settings have to be adjusted respectively depending on available flow and biomass type and quality (percentage of humidity and Lower Heating Value). At last, considering the electrical performance of the different RETs allow to find the best configuration for the specific load and site. It is not sufficient to have access to a power source if the production remains not reliable. This aspect regards also the voltage and frequency regulation, the required devices to convert DC into AC and the general measures to guarantee the continuity of the supply.

2.4.3. Storage systems

There are a number of different storage technologies based on different principles, but, for small scale systems up to some MW installed, *batteries* are the most used. This is mainly because battery storage is a mature technology that can be set for every plant size due to its incomparable modularity.

There are two types of batteries:

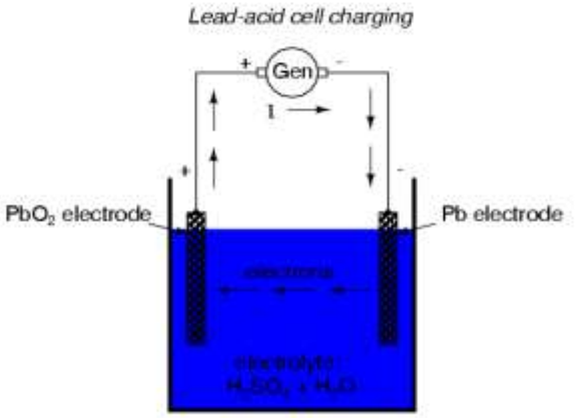
- Lead acid
- Lithium-ion

A *lead acid battery* could be synthetized in some basic components:

- A resilient plastic container
- Positive and negative internal plates made of lead
- Plate separators made of porous synthetic material
- Electrolyte, a dilute solution of sulphuric acid and water, known as *battery acid*
- Lead terminals, the connection point between battery and the device it powers.

Lead acid batteries operate in a constant process of charge and discharge. When a battery is connected to a load that needs electricity, current flows from the battery to the device. Vice versa, a battery becomes charged when current begins to flow back into it, restoring the chemical difference between the plates. The cycling ability of a battery is its possibility to be subjected repeatedly to discharging and charging processes. Depending on the depth of discharge (DOD), lead acid for deep cycle applications provides 200 to 300 discharge-charge cycles. The short life span of a lead acid battery depends mainly on grid corrosion on the positive electrode and expansion of the positive plates. This aging phenomenon is accelerated at elevated operating temperatures and when drawing high discharge currents.

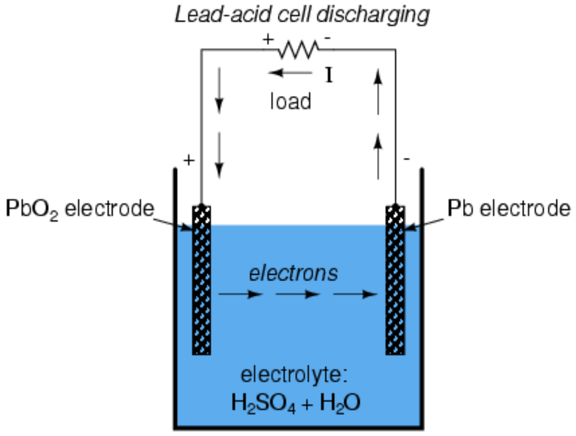
The reaction of the internal plates, positive and negative, with the sulphuric acid electrolyte produces a voltage. The lead dioxide plate reacts with H_2SO_4 to form lead sulphate, supplying electrons and remaining positive charged; the Pb plate reacts with sulphate ions to form lead sulphate. In this reaction, lead supplies two positive charges and is left negative. The reactions create a voltage and the supplying of energy too an external resistance discharges the battery.



At (+) electrode: $PbSO_4 + H_2O + O \longrightarrow PbO_2 + H_2SO_4$

At (-) electrode: $PbSO_4 + 2H \longrightarrow Pb + H_2SO_4$

FIGURE 21 LEAD-ACID CELL CHARGING



At (+) electrode: $Pb(IV)O_2 + 3H^+ + HSO_4^- + 2e^- \longrightarrow Pb(II)SO_4 + 2H_2O$

At (-) electrode: $Pb + HSO_4^- \longrightarrow Pb(II)SO_4 + H^+ + 2e^-$

Overall cell: $PbO_2 + Pb + 2H_2SO_4 \longrightarrow 2PbSO_4 + 2H_2O$

FIGURE 22 LEAD-ACID CELL DISCHARGING

The discharge reactions can be reversed by applying a voltage from a charging source. The inlet energy breaks down the lead sulphate and with oxygen from ionised water, lead oxide is deposited on the positive electrode, while lead is deposited on the negative electrode.

The chemistry of lead-acid batteries has been proven over more than 140 years, it is a really mature technology. Batteries of all shapes are available and starting from the 70's they begun to be sealed, with an advantage in using less electrolyte solution. The most significant benefit, however, is the ability to combine oxygen and hydrogen to create water and prevent dry out during cycling, which would be a heavy issue in arid climate environments. In their price range, lead-acid batteries provide the best value for energy per kilowatt-hour, the longest lifecycle and a large environmental advantage in that they are recycled at a very high rate: up to 97% of the lead is recycled and used in new batteries. They present the lowest self discharge among rechargeable batteries. On the other side, lead is heavier compared to alternative elements used in other technologies, so their weight-to-power ratio is poor. Furthermore, in lead-acid batteries the charging process is quite slow and repeated deep-cycling reduces battery life.

At first, lithium batteries had not ions, they were introduced at a second time. Lithium has the greatest electrochemical potential and provides the largest specific energy per weight. Rechargeable batteries with lithium metal on the anode could provide extremely high energy densities, but it was discovered that the cycling process produces undesired dendrites on the anode. Due to the instability of lithium metal, especially during the charging phase, made the scientists shift to a non-metallic solution using lithium ions. This is how the safe voltage and current is guaranteed in modern lithium based batteries.

The physical principle is the same, lithium-ion batteries use a positive electrode, the cathode, a negative electrode, the anode, and an electrolyte as conductor. The positive electrode is made of lithium metal oxide, while the negative electrode consists of porous carbon. During discharge, Li ions flow from the anode to the cathode through electrolyte and separator. The anode undergoes oxidation or loss of electrons, while cathode sees a gain of electrons, or a reduction. During charging, Li ions change their verse.

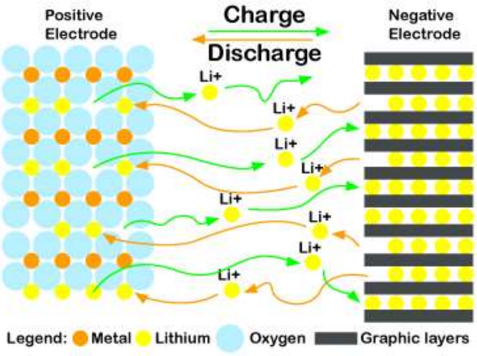


FIGURE 23 LI-ION CELL CHARGING/DISCHARGING

These batteries have high specific energy and commendable energy density, their charging process is rapid. They present a long shelf-life with no required maintenance and a very low self-discharge allowed. On the contrary, lithium-ion batteries need protection circuit to limit voltage and current and they degrades at high temperature. The heaviest constraint in developing countries remains the higher cost of these batteries if compared with other lead-based systems.

In the Table 6 there are sorted the most representative factors derived from a research made by a lithium-ion batteries producer [38].

	Lead acid (VRLA[4])	Lithium-ion
Energy density [Wh/l]	100	250
Specific energy [Wh/kg]	40	150
Regular maintenance	No	No
Initial cost [$/kWh]	120	600[5]
Cycle life	1200 @ 50% DoD	1900 @ 80% Dod
Temperature sensitivity	Degrades significantly above 25°C	Degrades significantly above 45°C
Efficiency	100% @20-hr rate 80% @4-hr rate 60% @1-hr rate	100% @20-hr rate 99% @4-hr rate 92% @1-hr rate

TABLE 6 BATTERY TECHNOLOGY COMPARISON

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[4] sealed/valve regulated lead-acid batteries

[5] There is a wide price range for lithium-ion, the value represents estimated price at moderate production volumes.

Chapter 3 STATE OF THE ART: ENERGY SIMULATIONS AND CROP WATER NEEDS CALCULATION

This section explains how energy simulation and water needs calculation can be run trough available computer tools. Energy systems could be simulated along a certain period and evaluated in terms of performance and costs.

The second part of the chapter explains how water is used by a crop from the physical point of view; then, the theoretical method to calculate water need for a certain crop is introduced and last part shows how the software tool CROPWAT works. Notions about the different irrigation techniques (paragraph 2.3.2) are used inside the computer program.

3.1. Energy Simulations

About the energy simulations, there are various simulation tools that could run energy plants to evaluate their technical and economical feasibility.

PVSYST

PVSYST [39] is a software tool for the sizing, simulation, and data analysis of a PV systems, designed to be used by architects, engineer, and researchers. It offers an extensive meteorological and PV components database, including inverters and MPPT devices.

HOMER Pro

The software studied for energy systems simulations is Homer Pro by NREL [40], which can model both grid-connected and off-grid micro-power systems and can simulate renewable and traditional (diesel) energy sources. Combining different power sources, it leads to the most cost effective solution that could save diesel, choosing from various dispatch strategies and taking into account the reliability of the system.

Data input required are

- the load curve during the year,
- system components,
- local energy resources in terms of availability,
- basic component costs,
- general maintenance costs,
- constraints like admissible shortage, minimum renewable fraction, emissions,
- lifetime and economics variables such as interest rate.

The program computes basic system design (components, peak power), installation and O&M costs during the lifetime of the system, it calculates yearly power production and fuel consumption. The modelling phase goes through three different stages: simulation, optimisation and sensitivity analysis.

The simulation phase consists in solving the energy balance equation for every hour of the year. Writing the balance underlining the reduction of fossil fuel consumption thanks to renewable sources would be as follow:

$$EE_{fossil} - EE_{ren} - EE_{battery} = Load\ [kWh]$$

If the system configuration can match the load in the hour analysed, within the constraints imposed, the simulation proceeds with the calculation of energy flows to and from each component of the system. If the configuration is not feasible, it is not considered. The user can introduce constraints about the minimum value of the load that has to be met, or the operating reserve that must be always available or the minimum primary energy saving obtainable with the new system.

The optimization carries out the simulation of all the possible system configurations and listing them in order of economical convenience, considering as best result the solution with lower Net Present Cost.
HOMER Pro allows repeating the optimization process for every sensitivity variable defined by the user (sensitivity analysis).

3.2. Water needs calculation

To evaluate water needs, it is required to understand how water is managed by a plant and how water is lost before reaching the roots. Moreover, irrigation could have different purposes, behind providing the plants with sufficient water to be able to grow. *Fertilising irrigation* is used to carry fertilising elements into the soil, in order to augment its growing properties. Water is the medium through which salts are dissolved. In contraposition with fertilising irrigation, the *leaching irrigation* occurs when water washes-out an excessive salt concentration in the root zone. A higher demand of water is required for each crop, only to fulfil the leaching purpose. *Pest controlling* irrigation is used to transport pesticides through water after dissolving them into the fluid. It could be used against both insects and bigger animals as moles.
There are many methods to evaluate water needs, manual calculation or simulation through computer programs. The one used to develop this work is CROPWAT 8.0 [27]. CROPWAT is a software tool created by Food and Agriculture Organisation, for the design and management of irrigation schemes. It allows the user to calculate some essential parameters using climate inputs and crop information.
The physical parameters that should be considered are the ones linked to water absorption and consumption. Soil humidity tends to decrease due to crop *evapotranspiration*, *percolation* and *surface runoff*. A quantity of water must be added to compensate losses and this quantity is the water requirement. To calculate it, the *potential evapotranspiration* ET_0, which is not directly measurable, should be known behind some climatic data of the region interested. Climate data are used to estimate a standard year, such as a virtual year whose climatic values are the average of the last years. With all these information about climate, soil and rainfall, the *Reference Evapotranspiration* (ET_C), which represents the potential evaporation of a well-watered grass crop, can be obtained [41].
The final results elaborated by the software are the crop water requirement and the irrigation scheduling. The user obtains a general schedule of the water required for the irrigation of every crop included in the simulation.
The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration, is called evapotranspiration (ET). *Evaporation* is the process whereby liquid water is converted to water vapour (vaporisation) and removed from the evaporating surface (vapour removal). The driving force to remove water vapour from the evaporating surface is the difference between the water vapour pressure at the evaporating surface and that of the surrounding atmosphere. As evaporation proceeds, the surrounding air becomes gradually saturated and the process slows down. It might stop if the wet air is not transferred to the atmosphere. The replacement of the saturated air with drier air depends greatly on wind speed. Hence, solar radiation, air temperature, air humidity and wind speed are climatological parameters to consider when assessing the evaporation process.
Transpiration consists of the vaporisation of liquid water contained in plant tissues and the vapour removal to the atmosphere. Crops predominately lose their water through stomata. These are small openings on the plant leaf through which gases and water vapour pass. The water, together with some nutrients, is taken up by the roots and transported through the plant. The vaporisation occurs within the leaf, namely in the intercellular spaces, and the vapour exchange with the atmosphere is controlled by the stomatal aperture. Nearly all water taken up is lost by transpiration and only a tiny fraction is used within the plant. Transpiration, like direct evaporation, depends on the energy supply, vapour pressure gradient and wind.
Evaporation and transpiration occur simultaneously. Apart from the water availability in the topsoil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and the crop canopy shades

more and more of the ground area. When the crop is small, water is predominately lost by soil evaporation, but once the crop is well developed and completely covers the soil, transpiration becomes the main process. The evapotranspiration rate from a reference surface, full of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ET_0. The reference surface is a hypothetical grass reference crop with specific characteristics. The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. If water is available without any limit at the reference evapotranspiring surface, soil factors do not affect ET. Relating ET to a specific surface provides a reference to which ET from other surfaces can be related. It obviates the need to define a separate ET level for each crop and stage of growth. ET_0 values measured or calculated at different locations or in different seasons are comparable as they refer to the ET from the same reference surface.

The only factors that could vary ET_0 are climatic parameters. Consequently, ET_0 is a climatic parameter and can be calculated from weather data. ET_0 expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors. The FAO Penman-Monteith method is recommended as the sole method for determining ET_0, according to [41]. The method has been selected because it closely approximates grass ET_0 at the location evaluated, is physically based, and explicitly incorporates both physiological and aerodynamic parameters.

The amount of water required to compensate the evapotranspiration loss from the cropped field is defined as crop water requirement (CWR). Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration. The irrigation water requirement basically represents the difference between the crop water requirement and effective precipitation.

After a detailed description of the Penman-Monteith method, the following paragraphs describe the components of CROPWAT, the software tool that calculates ET_C.

3.2.1. ET$_0$ calculation - FAO Penman-Monteith method

As explained before, the concept of ET_0 was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. As water is abundantly available at the reference evapotranspiring surface, soil factors do not affect ET_0. Relating the evapotranspiration process to a specific surface provides a reference to which evapotranspiration from other surfaces can be related. It obviates the need to define a separate evapotranspiration level for each crop and stage of growth. ET_0 is a climatic parameter and can be computed from weather data. The method of calculation selected is the FAO Penman-Monteith, and it has been demonstrated through many years of evaluations reported in scientific literature. The FAO Penman-Monteith equation is a close, simple representation of the physical and physiological factors governing the evapotranspiration process. This method explicitly incorporates both physiological and aerodynamic parameters. Moreover, procedures have been developed for using this method even with limited climatic data, as it happens in developing countries.

A consultation of experts and researchers was organised by FAO in 1990, in collaboration with the International Commission for Irrigation and Drainage and with the World Meteorological Organisation, to review the FAO methodologies on crop water requirements and to advise on the revision and update of procedures.

The panel of experts recommended the adoption of the Penman-Monteith combination method as a new standard for reference evapotranspiration and advised on procedures for calculation of the various parameters. The reference crop was defined as a hypothetical crop with an assumed height of 0.12 m, having a surface resistance of 70 s m-1 and an albedo of 0.23, closely resembling the evaporation of an extension surface of *green grass* of uniform height, actively growing and adequately watered. The method overcomes shortcomings of the previous FAO Penman method and provides values more consistent with actual crop water use data worldwide-[30].

From the original Penman-Monteith equation and the equations of the aerodynamic and surface resistance, the FAO Penman-Monteith method to estimate ET_0 is expressed as:

$$ETo = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \dfrac{900}{T+273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0{,}34 \cdot u_2)}$$

Where:

ET_0	reference evapotranspiration $\left[\frac{mm}{day}\right]$,
R_n	net radiation at the crop surface $\left[\frac{MJ}{m^2 day}\right]$,
G	soil heat flux density $\left[\frac{MJ}{m^2 day}\right]$,
T	mean daily air temperature at 2 m height [°C],
u_2	wind speed at 2 m height $\left[\frac{m}{s}\right]$
e_s	saturation vapour pressure $[kPa]$,
e_a	actual vapour pressure $[kPa]$,
$e_s - e_a$	saturation vapour pressure deficit $[kPa]$,
Δ	slope vapour pressure curve $\left[\frac{kPa}{°C}\right]$,
γ	psychrometric constant $\left[\frac{kPa}{°C}\right]$.

The reference evapotranspiration ET_0, provides a standard to which:

- evapotranspiration at different periods of the year or in other regions can be compared;
- evapotranspiration of other crops can be related.

The equation uses standard climatological records of solar radiation (sunshine), air temperature, humidity and wind speed. To ensure the integrity of computations, the weather measurements should be made at 2m (or converted to that height) above an extensive surface of green grass, shading the ground and not short of water.

No weather-based evapotranspiration equation can be expected to predict evapotranspiration perfectly under every climatic situation due to simplification in formulation and errors in data measurement. It is probable that precision instruments under excellent environmental and biological management conditions will show the FAO Penman-Monteith equation to deviate at times from true measurements of grass ET_0. However, the Expert Consultation agreed to use the hypothetical reference definition of the FAO Penman-Monteith equation as the definition for grass ET_0 when deriving and expressing crop coefficients. In next section, the terms *crop coefficient* are explained in detail.

3.2.2. The crop coefficient approach

By using the FAO Penman-Monteith definition for ET_0, it is possible to calculate crop coefficients (K_C) at research sites by relating the measured crop *evapotranspiration under standard conditions* (ET_C) with the calculated ET_0, i

$$K_C = \frac{ET_C}{ET_0}$$

ET_C is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions and achieving full production under the given climatic conditions. It represents the ideal case. The effects of various weather conditions are incorporated in ET_0, the different characteristics that distinguish the cropped surface from the reference surface are considered into the crop coefficient. Two calculation approaches exist to determine ET_C, the single and the dual crop coefficient approach. The first one takes together the difference in evapotranspiration between the crop and reference grass, instead in the second approach, the crop coefficient is split into two factors describing separately the difference in evaporation and transpiration between the same two surfaces. The single crop coefficient approach is used for most applications related to irrigation planning, design, and management. The dual crop coefficient approach is relevant in calculations where detailed estimates of soil water evaporation are required, such as in real time irrigation scheduling applications, water quality modelling, and in research.

The crop evapotranspiration differs distinctly from the reference evapotranspiration (ET_0) as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass. In the crop coefficient approach, those differences are accounted within the crop coefficient. The K_C factor serves as an aggregation of the physical and physiological differences between crops and the reference definition [30]. Differences in leaf anatomy, stomatal characteristics, aerodynamic properties and even albedo cause the crop evapotranspiration to differ from the reference crop evapotranspiration under the same climatic conditions. Due to variations in the crop characteristics throughout its growing season, K_C for a given crop changes from sowing until harvest.

K_C is basically the ratio of the crop K_C and the reference ET_0 and it represents an integration of the effects of four primary characteristics that make the crop vary from reference grass:

- *Crop height*: it influences the aerodynamic resistance term of the FAO Penman-Monteith equation and the turbulent transfer of vapour from the crop into the atmosphere.
- *Albedo* (reflectance) *of the crop-soil surface*: the albedo is affected by the fraction of ground covered by vegetation and by the soil surface wetness. The albedo of the crop-soil surface influences the net radiation of the surface, R_n in Penman-Monteith equation, which is the primary source of the energy exchange for the evaporation process.
- *Canopy resistance:* the resistance of crop to vapour transfer is affected by leaf area (number of stomata), leaf age and condition, and the degree of stomatal control. The canopy resistance influences the surface resistance, r_s in Penman-Monteith equation.
- *Evaporation from soil*, especially exposed soil.

3.2.3. CROPWAT modules

In order to calculate the parameters like ET_C, CROPWAT requires information and inputs. They are inserted through different modules, some ones linked to climate data, some others linked to crop type, others about soil characteristics.

Rain module

The Rain module is primary for data input, requiring information on the precipitation values on a monthly, decade or daily basis.

This module also include calculations, producing Effective rainfall data, defined as the portion of rainfall that can be used by a plant, using one of the approaches available, which are [30]:

- Fixed percentage of rainfall
- Dependable Rain
- Empirical formula
- USDA Soil Conservation Service Method

Fixed percentage

In general, the efficiency of rainfall decreases with increasing rainfall. For most rainfall values below $100\frac{mm}{month}$, the efficiency will be approximately 80%. The fixed percentage is an input given by the user to account for the losses due to surface runoff and deep percolation.

Dependable rain

The method is based on a formula developed in the Water Service of FAO, after an analysis carried out for different arid and sub-humid climates. The formula tries to estimate the dependable rainfall and the losses due to DP – deep percolation - and RO – surface runoff:

$P_{eff,month} = 0.6 \cdot P_{month} - 10 \qquad for\ P_{month} \leq 70mm$

$P_{eff,month} = 0.8 \cdot P_{month} - 24 \qquad for\ P_{month} > 70mm$

[monthly step]

$P_{eff,dec} = 0.6 \cdot P_{dec} - 10 \qquad for\ P_{dec} \leq \frac{70}{3}mm$

$P_{eff,dec} = 0.8 \cdot P_{dec} - \frac{24}{3} \qquad for\ P_{dec} > \frac{70}{3}mm$

[decadal rainfall data]

Empirical formula

The formula is the same of the Dependable rainfall, but parameters are variables and they can be determined from local climatic records:

$P_{eff,month} = a \cdot P_{month} - b \qquad for\ P_{month} \leq z\ mm$

$P_{eff,month} = c \cdot P_{month} - d \qquad for\ P_{month} > z\ mm$

[monthly step]

$P_{eff,dec} = a \cdot P_{dec} - \frac{b}{3} \qquad for\ P_{dec} \leq \frac{z}{3}\ mm$

$P_{eff,dec} = c \cdot P_{dec} - \frac{d}{3} \qquad for\ P_{dec} > \frac{z}{3}\ mm$

[decadal rainfall data]

USDA Soil Conservation Service

The formula developed by USCS is

$P_{eff,month} = \frac{P_{month} \cdot (125 - 0.2 \cdot P_{month})}{125} \qquad for\ P_{month} \leq 250\ mm$

$P_{eff,month} = 125 + 0.1 \cdot P_{month} \qquad for\ P_{month} > 250\ mm$

[monthly step]

$P_{eff,dec} = \frac{P_{dec} \cdot (125 - 0.6 \cdot P_{dec})}{125} \qquad for\ P_{dec} \leq \frac{250}{3}\ mm$

$P_{eff,dec} = \frac{125}{3} + 0.1 \cdot P_{dec} \qquad for\ P_{month} > \frac{250}{3}\ mm$

[Decade step]

Climate module

Climatic data should be collected from the nearest and most representative meteorological station. An important step is the conversion required to adjust the data into the format accepted by CROPWAT. The information required are:

- Temperature data: maximum and minimum temperature $[°C]$;
- Humidity data: average daily Relative Humidity [in percentage] or vapour pressure $[kPa]$;
- Sunshine data: sunshine hours or sunshine percentage; sunshine represents the duration of the daylight without clouds. Apart from the cloudiness, it depends on the position of the sun and is hence a function of latitude and day of the year. It is expressed as hours of sunshine $[hours]$, as a percentage of daylight $[\%]$ or as fraction of daylight $[-]$;
- Wind speed data: average daily wind speed in $\left[\frac{km}{day}\right]$ or $\left[\frac{m}{s}\right]$.

CROPWAT 8.0 can calculate reference ET_0 using only temperature, but humidity, wind speed and sunshine should be entered if available. On the base of climatic data available, the program estimates also the solar radiation reaching soil surface. This quantity depends on latitude, date and time of the day. Solar radiation (R_s), computed in CROPWAT calculations, represents the amount of extra-terrestrial radiation reaching a horizontal plane on soil surface, that is computing the fraction of extra-terrestrial radiation scattered, reflected or absorbed by the atmospheric gases, clouds and dust. Part of the solar radiation is reflected from the soil surface (R_{sr}), part is absorbed (R_{abss}). Radiation is expressed in $\left[\frac{MJ}{m^2 day}\right]$.

Crop module

The crop type and its stage of development should be considered when calculating the evapotranspiration for an ideal situation, without water stress, in well-managed fields. Every characteristic of a crop, such as its height, its rooting depth, its roughness, ground cover, has an impact on the ET_C value, even if climatic conditions are the same for different crops. The software needs to know which type of crop is being evaluated and CROPWAT 8.0 has crop data for several common crops taken from several FAO publications, as “Crop evapotranspiration - Guidelines for computing crop water requirements” featuring in [30] and [42].

Soil module

The Soil module is essentially data input, requiring the following parameters:

- Total Available Water (TAW);
- Maximum infiltration rate;
- Maximum rooting depth;
- Initial soil moisture depletion.

This module also includes calculations, providing the *Initial available soil moisture*.

The TAW represents the water contained in the soil that can be used by a crop. It is defined as the difference between Field Capacity (FC) and Wilting Point (WP), where FC is the amount of water that a well drained soil holds against gravitational forces and WP is a condition that occurs when plants can no longer exert enough force to extract the remaining soil water. There is no water available for the plants above the FC level as water cannot be held against the force of gravity and it naturally drains as deep percolation (DP). TAW depends on texture, structure and organic matter content of the soil. It is expressed in mm per meter of soil depth. The Readily Available Water (RAW) is the fraction of Total Available Water (TAW) that a crop can extract from the root zone without suffering water stress.

Although water is theoretically available to the plants up to a water tension equivalent to the Wilting Point (WP), crop water uptake is reduced well before that point is reached. When the soil is sufficiently wet, soil water can meet the atmospheric demand of the crop, and water uptake equals the Crop evapotranspiration under standard conditions ET_C . As the soil water content decreases, water becomes more strongly bound to the soil matrix and is more difficult to extract. When the soil water content drops below a threshold value, identified through the *critical depletion fraction* (p), soil water can no longer be transported quickly enough towards the roots to respond to the evapotranspiration demand and the crop begins to experience stress. A list of common p values is available in [30] at Chapter 8 - table 22.

The image below (Figure 24) shows an ideal volume of soil with all the elements of water balance.

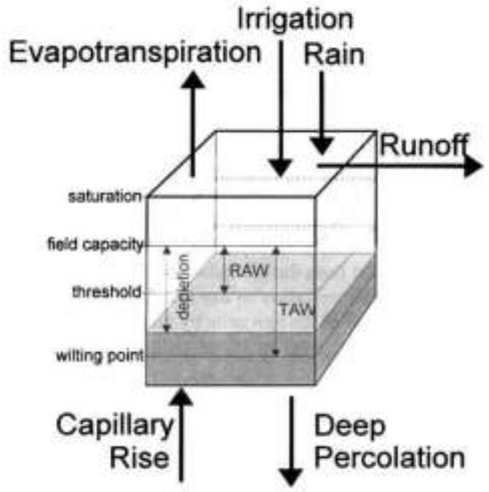


FIGURE 24 VOLUME UNIT OF THE ROOT ZONE

The maximum infiltration rate, expressed in mm per day, represents the water depth that can infiltrate in the soil over a 24 hours period, as a function of soil class, soil type and rain or irrigation intensity. It allows evaluating the surface runoff (RO), occurring when water intensity overcomes the infiltration capacity of the soil.

The third parameter is often a crop characteristic, although in few cases the soil can affect the maximum rooting depth. The Maximum rooting depth is expressed in centimetres. Default value is set arbitrarily on 900cm, indicating soil having no significant characteristics that can restrict root growth. Any value lower than crop rooting depth would indicate a limitation to root growth. Root depth is important to determine the water a crop can collect, indeed water is physically available for a plant only until the roots are able to attract it. For this reason, to evaluate RAW_i, it appears also z_i, root depth.

At last, initial soil moisture is a parameter that indicates the water content at the beginning of the growing season, which is seeding for non-rice crops and land preparation in case of rice cultivation. It is expressed as a percentage of TAW, in terms of depletion of FC. The default value of 0% represents a fully wetted soil, 100% is a dry soil at the WP. In most cases only an estimate can be done, depending on previous crop or fallow period and dry season.

Those parameters are partially available in some studies carried out by FAO, such as [30] - Chapter 7, ET_C under soil water stress conditions - there is a table which lists “Typical soil water characteristics for different soil types”. It contains FC and WP values for different soil types: sand, loamy sand, sandy loam, loam, silt loam, silt, silt clay loam, silty clay, clay. In [43] Annex 2 Infiltration rate and infiltration test, there is a list of basic infiltration rates for various soil types.

Crop pattern module

The module requires information on the crops being part of the scheme, for each crop the user has to define:

- *Crop file*, which contains information about the crop as crop coefficient K_C and rooting depth;
- Planting date, normally determined from climatic conditions and from farmer experience;
- Area, extension of the area dedicated to each crop, as a percentage of the total cropped area.

CWR module

The Crop Water Requirement module includes calculations, producing the amount of water needed by each crop on a decade basis and over the total growing season. It is calculated as the difference between crop evapotranspiration under standard conditions (ET_C) and the effective rainfall P_{eff}.

In theory, ET_C and CWR are identical, but while ET_C is the amount of water that is lost due to evapotranspiration, CWR is the quantity of water that needs to be supplied. Knowing the Reference evapotranspiration of each crop, the crop coefficient approach is used to determine ET_C, which differs from ET_0 as described in paragraph "Crop coefficient approach" (section 3.2.2). In CROPWAT 8.0, the calculation of CWR is carried out on a decade basis. To convert monthly rainfall data to decade values, the software performs a linear interpolation: values for first and third decades of each month are calculated by interpolation with the preceding and successive month respectively. To compensate for deviations in the maximum and minimum months, a reiteration is carried out to fulfil the condition that the three decade values average gives exactly the given monthly average.

Crop water requirements are then calculated as the difference between crop evapotranspiration and effective rainfall.

Irrigation is required when rainfall is insufficient to compensate for the water lost by evapotranspiration. The primary objective of irrigation is to apply water at the right period and in the right amount. By calculating the soil water balance of the root zone on a daily basis, the timing and the depth of future irrigations can be planned. In Figure 24, the root zone is presented by means of a container in which the water content may fluctuate. The daily water balance, expressed in terms of depletion at the end of the day is:

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i - CR_i + ET_{c,i} + DP_i$$

Where:

$D_{r,i}$	root zone depletion at the end of day i [mm]
$D_{r,i-1}$	water content in the root zone at the end of the previous day, i-1 [mm]
P_i	precipitation on day i [mm]
RO_i	runoff from the soil surface on day i [mm]
I_i	net irrigation depth on day i that infiltrates the soil [mm]
CR_i	capillary rise from the groundwater table on day i [mm]
$ET_{C,i}$	crop evapotranspiration on day i [mm]
DP_i	water loss out of the root zone by deep percolation on day i [mm]

CROPWAT 8.0 computes a daily water balance of the root zone as described by the equation. It is assumed that RO_i occurs each time P_i exceeds the Maximum infiltration rate. DP_i is estimated to occur each time the available soil moisture content in the root zone exceeds Field Capacity (FC). Since precipitation losses are determined through RO_i and DP_i, total and not effective precipitation is used in the soil water balance.

Net irrigation water requirement is therefore equal to the root zone depletion. To avoid crop water stress, irrigation should be applied before the moment the readily available water is depleted. To avoid deep percolation losses, the net irrigation depth should be smaller than or equal to the root zone depletion.

Scheme module

This module includes calculations, producing irrigation requirement for each crop of the scheme, net scheme irrigation requirement, irrigated area as a percentage of the total area and irrigation requirement for the actual area.

The first value is a quantity already seen in previous paragraphs, but it should be taken in consideration that it does not take into consideration soil water contribution to the crop. The net scheme irrigation requirement computes the total irrigation water needs at scheme level over a certain time step. In the Scheme module, the Net scheme irrigation requirement is calculated on a monthly basis taking into account the Irrigation requirements of the crops in the field over the period under analysis and the correspondent cropped area. It is expressed in average $\left[\frac{mm}{day}\right]$, in $\left[\frac{mm}{month}\right]$ and in $\left[\frac{l}{s \cdot ha}\right]$.

As the net and not the gross irrigation requirement is considered, this value does not take into account water losses occurring at system level. Then, according to planting and harvesting dates and to the percentage of each cropped area, irrigated area is calculated with the total irrigation demand for this area.

Schedule module

The last module is the schedule module, which includes calculation and solves the soil water balance on a daily step. Thanks to this quantity, the user can develop indicative irrigation schedules to improve water management, evaluate the current irrigation practices and their effectiveness, develop alternative water delivery schedules under restricted water supply conditions and evaluate crop production under rain fed conditions or assess supplementary irrigation.

The following parameters are used in the soil water balance:

- *Rainfall*: total and not effective rainfall is used for water balance calculations, since losses due to DP and RO are evaluated respectively through Soil Moisture Content in the root zone and Maximum Infiltration Rate, which are soil data input. That is the reason why Effective rainfall during growing period could be different if compared to Effective rainfall calculated in the Rain module (with one of the four available methods, e.g. fixed percentage). Monthly rainfall data are divided up in three decades; in order to simulate the non-continuous distribution of rainfall events, decade rainfall values are divided in two episodes, one on the third and one on the seventh days of each 10-days period.
- *Water stress coefficient* (K_S): it allows to describe the effect of soil water deficit on crop evapotranspiration, which is assumed to decrease linearly (Figure 25) in proportion to the reduction of water available in the root zone. K_S is given by:

$$K_S = \frac{TAW - D_r}{TAW - RAW}$$

Where TAW is the total available soil water
D_r is the root zone depletion
RAW is the readily available soil water

The estimation of K_S requires a daily water balance computation for the root zone.

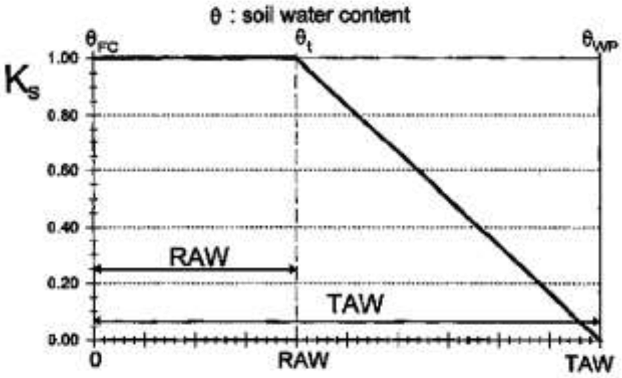


FIGURE 25 WATER STRESS COEFFICIENT

- *Crop evapotranspiration under non-standard conditions* ($\mathrm{ET}_{\mathrm{C,adj}}$): it is the evapotranspiration from crops grown under environmental conditions that differ from the standard optimal conditions. When cultivating crops in fields, the real crop evapotranspiration may deviate from Crop evapotranspiration under standard conditions ET_{C} due to non-optimal conditions. These variations could be water shortage, but also presence of pest and diseases, soil salinity, low soil fertility or waterlogging. This may result in scanty plant growth, low plant density and reduction in final production. Forces acting on the soil water decrease its potential energy and make it less available for plant root extraction. When the soil is wet, the water has a high potential energy, is relatively free to move and is easily taken up by the plant roots. In dry soils, the water has a low potential energy and is strongly bound by capillary and absorptive forces to the soil matrix, and is less easily extracted by the crop.

  CROPWAT 8.0 includes a simple approach to account for the effect of sub-optimal soil moisture conditions. $\mathrm{ET}_{\mathrm{C,adj}}$ due to water shortage is calculated by mean of the Crop water stress coefficient (K_S) according to the following equation:

$$ET_{C,adj} = ET_C \cdot K_S$$

- *Root zone depletion* (D_r): it represents the water shortage relative to Field Capacity (FC). It can be expressed as a percentage or in mm over the rooting depth. Although following heavy rain or irrigation the water content in the soil might temporally exceed FC, it is assumed that the total amount of water above FC is lost the same day by Deep Percolation (DP). Considering the root zone at FC following heavy rain or irrigation, the minimum value for D_r is zero. Because of evapotranspiration, the water content in the root zone gradually decreases, while D_r increases. In the absence of any wetting event, the water content will steadily reach its minimum value at Wilting Point (WP). At that moment, no water is left for evapotranspiration and D_r has reached its maximum value, equals to the TAW.
  The limits imposed on Dr are consequently:
  $$0 \leq Dr \leq TAW$$
- *Irrigation efficiency*: inadequacies of the irrigation system, such as poor land levelling, poor practices in field in case of gravity irrigation methods, can cause irrigation water losses. To account the water volumes that do not remain within the root zone, CROPWAT 8.0 allows to input the estimation of irrigation efficiency, through which estimates the Net irrigation depth.
  A default value of 70 % is recommended for normal well-managed gravity irrigation and lined canals.
- *Net irrigation:* it represents the water depth (expressed in mm) that is used beneficially. It is calculated as the product of the Gross irrigation depth by the Irrigation efficiency.
- Deficit: amount of water [mm] below field capacity.
- *Irrigation losses:* irrigation water reaching the root zone, that is Net irrigation, is not always advantageously used by the crop. In case the Net irrigation contribution brings the soil moisture content to exceed the Field Capacity (FC), the amount of water above FC is assumed to be lost by DP. This irrigation depth exceeding FC is computed as Irrigation losses.
  In the Soil water balance of the Schedule module, Irrigation losses are calculated on a daily basis and summed up over the growing season as Total irrigation losses. Note that Irrigation losses do not refer to the difference between Gross irrigation and Net irrigation, representing the irrigation water fraction that does not reach the root zone, computed through the Irrigation efficiency.
- *Gross irrigation:* it represents the water depth (expressed in mm) applied to the field. Since the Irrigation efficiency is usually lower than 100 %, only a fraction of the Gross irrigation depth, that is, the Net irrigation depth, effectively reaches crop root zone.
- *Flow*: it represents the continuous water discharge needed to satisfy crop irrigation requirements over the irrigation interval period. It is expressed in litre per second per hectare and calculated converting the Gross irrigation application depth into a permanent supply.

The calculation of the Net Irrigation or the Crop Water Requirement, on a decade basis or either on monthly basis, is not sufficient to develop a satisfactory supply planning. It is required to find technical elements related to how to ensure the water supply. The element to calculate is the *irrigation volume*. It is the amount of water that should be given to soil at every irrigation action to refill it to optimal condition, without waste. The optimal condition is field capacity. The actions take place whenever RAW is reached by soil due to crops water absorption. The root depth for each crop, behind TAW and critical depletion fraction, gives the depth of irrigation water. When $D_{r,i}$ reaches the threshold value below which water is no more readily available (the minimum value), irrigation should occur. If TAW is calculated in relation to the soil type, it is independent by crops; on the contrary, RAW depends on crop type by two parameters: root depth and critical depletion fraction. Below RAW_i, water is still present in the soil, but it is extracted with higher resistance and the plant goes into water stress. Theoretically, irrigation should avoid stress conditions, so water should be supplied when soil water content reaches the threshold value. The net water volume is exactly equal to RAW_i in order to fill the soil until its field capacity. Through irrigation efficiencies, the calculations go on to find the gross water volume and, with the daily water consumption of each crop, the number of days that intercourse between two following irrigation actions. If water consumption $[F_i]$, which is a result of the scheme module, is expressed in $\left[\frac{mm}{day}\right]$ and RAW_i is expressed in $[mm]$, irrigation frequency is in $[days]$.

$$TAW = (FC - WP)$$

$$RAW_i = TAW_i \cdot z_i \cdot p_i$$

$$T_i = \frac{RAW_i}{F_i}$$

F_i varies from month to month and depending on the crops cultivated during each month. In order to design the distribution network and the pumping system, the worst month in terms of water request should give be the nominal variable which is flowrate. This variable is calculated through a method reported in [44]. The flowrate value could be obtained for the month with highest demand, but flowrate calculation refers to the entire growing season. It must be noticed that in reality, it is not recommended to maintain the irrigation frequency T_i constant, because this method does not take into consideration the effective hydrologic and physiologic needs of the plants. Nevertheless, it may be used to evaluate the flowrate needed to size the distribution network and the pumping system. It refers to the maximum request and under the assumption not to have water stress for any crop, in order to meet the highest demand. The procedure is repeated for every irrigation system chosen. The flowrate is calculated as shown below: first, it is obtained the number of irrigation actions “n” to satisfy the water needs during the whole crop growing season, the specific flowrate [l/s/ha] as if the supply was continuous; then, Q_i depending on the delivery time or the length of an irrigation action, as follow:

$$n_i = \frac{N_i}{T_i}$$

$$i_i = \frac{n_i \cdot RAW_{i,gross}}{N_i} \cdot \frac{10000}{24 \cdot 3600} \left[\frac{l}{s \cdot ha}\right]$$

$$Q_i = \frac{24 \cdot T_i \cdot S_i \cdot i_i}{t} \left[\frac{l}{s}\right]$$

Where: N_i number of days of growing period
S_i is the surface cultivated by crop *i*
t is the delivery time

Chapter 4 THE CASE STUDY

All the considerations made for the Water Energy Food nexus are reported to a case study in Eritrea. In the first part of the chapter, the country is presented through its history that strongly affected its path to development, its energy sector, still unreliable and for most of the population not accessible, and finally its geographical and climatic characteristics.
For the place of interest, a farm located in a rural area not connected to the national energy grid, the context and the general current situation is analysed in the first section. The current situation about irrigation and water management is described, with a specific focus on the actual energy consumption linked to the irrigation system. Next part is about the traditional design of a new energy system to pump and distribute the irrigation water, considering a load curve elaborated relying only on farmers' assumptions, without considering a study on the effective crops water needs. At the end, the energy load demand is evaluated in a new way, considering the WEF nexus and the connections between water needs, irrigation techniques and energy request. Results and comparisons show the difference among the three approaches.

4.1. The Eritrean general context

4.1.1. History

FIGURE 26 ERITREA MAP

At the beginning of its history, Eritrea was linked with Ethiopia, as it was its northern province since 10th century AD. At that time, it was administered by a governor, until in the 16th century when Eritrea fell to the Ottoman Turks empire. For three centuries Massawa, the main coastal city, has remained in the hands of the Turks, but from 1869 the Suez Canal was opened and Red Sea was accessible to Mediterranean traffic. During the following years, Italy firstly acquired some stretches of coastline in the South and then these pieces of land became part of the Italian state. Eritrea opposed little resistance as locals moved towards the Ethiopian highlands. The Ethiopians' king made an alliance with Italians that failed to conquer the entire Ethiopia in 1896 and remained in Eritrea from 1897 to 1941 as colons. During this period, Italy sent out tens of thousands of Italian settlers, developing road and rail transport, but as with all European colonies in Africa, little was done to improve the conditions nor education of the Eritreans. The Italian presence in Eritrea increased rapidly from 1935, when Massawa became the main point of entry for the forces assembling for the planned invasion of Ethiopia. When the conquer has been completed, Eritrea took its place as one part of the new *Italian East Africa.*

When Italy entered World War II as one of the Axis powers, in 1940, Italian East Africa became a target for the Allies. The next year British forces moved from Sudan into western Eritrea. British and Ethiopian forces accomplished the final defeat of Italian East Africa when they entered Addis Ababa in May. Ethiopia was brought back under the rule of Haile Selaissie, while British provided a temporary administration of Eritrea. During this time, a bloody feud was carried on by British to force the remaining Italians to leave the country. Nevertheless, even the British administration was destined to fail. In 1945, Heile Selassie showed his need for an access to the sea through the possession of Eritrea to President Roosvelt. In 1950, UN decision was that Eritrea should become part of Ethiopia from 1952 as an autonomous federal province with its own constitution and elected government. USA interest in Eritrea was moved by the chance of a naval base in the Red Sea. Inside the country, there were divided opinions and the first government was therefore at first a coalition between the *Unionists* – financed by Addis Ababa – and the *Muslim League*, supporting the independence. Aware that there would be continuing agitation for independence, Haile Selassie shamelessly interfered to secure his aim of union. With his help the Unionists removed Muslims from government jobs, putted an end to teaching in Arabic and banned all other political parties (1958) and trade unions (1959), introducing Ethiopian law and even giving the Eritrean government a new name. It became merely the Eritrean *administration*. On a unanimous vote in both Addis Ababa and Asmara, Eritrea's federal status within Ethiopia was decided to be abolished. The area had to become a province like any other in the Ethiopian empire. In 1960, Eritrea's Muslim leaders, living in exile, formed the ELF or *Eritrean Liberation Front* to fight for independence. By the mid-1960s, they had a guerrilla force operating in western Eritrea and in a few years, they ceased to be a purely Muslim movement. After the union of 1962, Haile Selassie interfered in Tigre's schools (a region of Eritrea), banning Tigrinya, the local language, and replacing it with Amharic. This converted many Tigre Christians to the cause of independence.

Eventually, after bitter disputes and even outright warfare between rival factions in the Eritrean independence movement, a single powerful group emerged as a distant offshoot of the original ELF. This is the EPLF, or *Eritrean People's Liberation Front*. The EPLF was offered an unexpected chance to achieve its aims in 1974, when Ethiopia is convulsed by a major upheaval: the toppling of Haile Selassie and subsequent three years of conflict for power. All the major towns in Eritrea were freed from Ethiopian control. This situation last only until 1978 when Mengistu’s group was the winning one in the Ethiopian political scene. At the same time, the USSR rushed in to claim Ethiopia (previously a client state of the USA) for its own side in the Cold War. It was again about the control of the valuable Red Sea port of Massawa. With a plentiful supply of Soviet arms, it was easy for Mengistu to recover the towns of Eritrea, but even for a well supplied conventional army it is difficult to suppress entirely a dedicated group of guerrillas. The EPLF, controlling much of the countryside, were able to keep Ethiopia in a continuous and costly state of warfare on its northern border. The beginning of the end for Mengistu was in 1987, when the Eritrean guerrillas, the EPLF, were strong enough to move south past Nakfa into the highlands of Ethiopia. In 1988, they joined forces with another Marxist group fighting for regional independence, the TPLF or *Tigre People's Liberation Front*. In 1990, in the most crucial step of all, they captured Massawa, cutting off Ethiopia's link with the sea. Meanwhile the TPLF have merged with yet another guerrilla organisation to form the EPRDF or *Ethiopian People's Revolutionary Democratic Front*. By May 1991, it was clear that there was nothing to prevent the rebels reaching Addis Ababa. Mengistu fled the country. The EPRDF took power, under its chairman Meles Zenawi. He promised a new form of government guaranteeing rights (even to the point of secession) to regional minorities. Implicitly Eritrea's claim to independence was included.

In a referendum, held in April 1993, the votes cast for Eritrean independence were more than 99% of the total. The secretary-general of the EPLF, Isaias Afwerki, became president of a *transitional* government. In 1994, the EPLF completed its transformation from a guerrilla organisation to a political party. It was known as the PFDJ or *People's Front for Democracy and Justice*. This remains for the rest of the decade the only political party in Eritrea. There was much talk of allowing other parties to function, but the PFDJ - determined to avoid reopening old wounds - bans any party with a purely ethnic or religious base, which seemed to cover all the candidates. Eritrea unexpectedly maintained good relations with Ethiopia, in the continuing spirit of ease the path to independence. Trade flourished between the two countries, particularly after customs duties were abolished in 1995 on their mutual border.

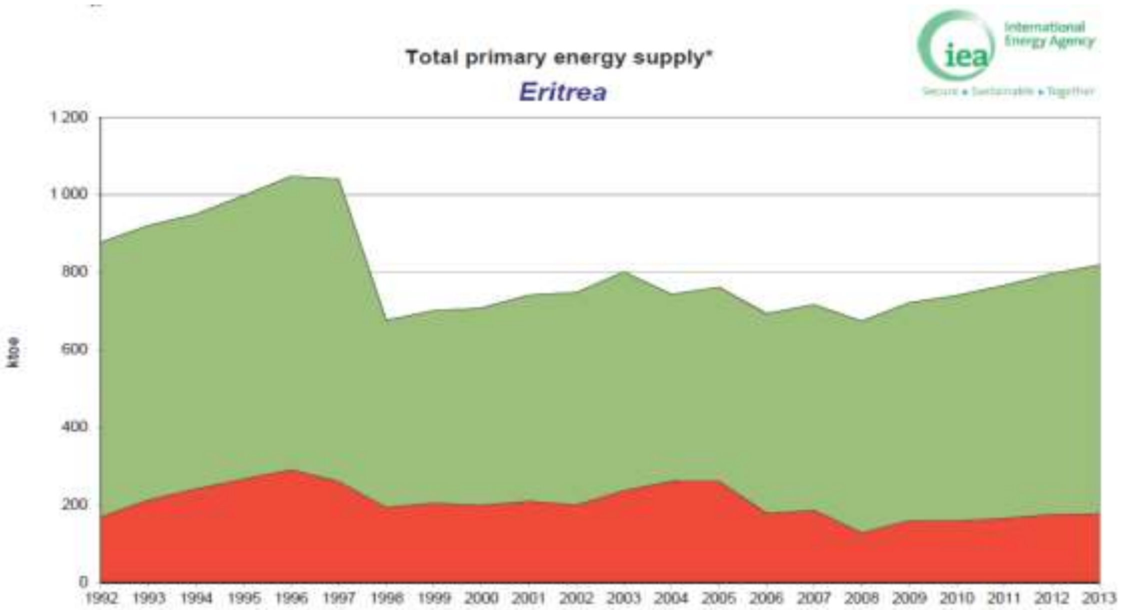
Nevertheless, in 1998 conflict with Ethiopia became, once again, the central fact of Eritrean life. Relations between Ethiopia and Eritrea begun to turn sour after Eritrea introduced its own currency, the *nakfa*, in November 1997. Until this time, it had continued to use the Ethiopian *birr*. Eritrea declared the nakfa to be of equal value to the birr and expected its trade with Ethiopia (70% of its total exports) to continue uninterrupted. Ethiopia insisted, instead, that all transactions between the two nations should henceforth be in hard foreign currency. Although this restriction harmed both nations' economies, it was far from being a cause for renewed war. Nor was the small incident, which actually reignited the long but apparently resolved conflict between the two countries. In May 1998, there was an incident in the town of Badme, in Tigre, just on the Ethiopian side of a disputed section of the border. Gunfire was exchanged between Ethiopian police officers and a group of armed intruders from Eritrea. In spite of international mediation, the conflict escalated into full-scale war. Being a war along a border, it developed like World War I did. Trenches, mines, the unimportant desert town of Badme was taken and retaken like a symbolic trophy. By mid-1999, it is calculated that in the confronting armies a number of around 400000 men and that 50000 soldiers have died. The costly stalemate continued until May 2000, when Ethiopia won large tracts of land in a sudden push. War was over, peace talks begun in Algeria in June. The situation turned to “normality”, but the countries have had no contacts since that year.

Isaias Afewerki has been the only Eritrean President since 1994.

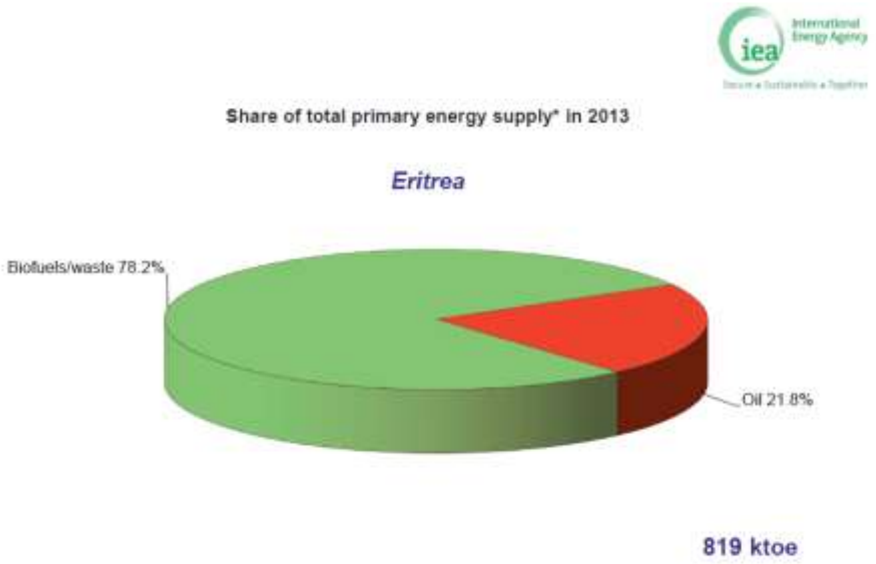
4.1.2. Energy context

As in most of African and in particular Sub Saharan countries, in many rural areas of Eritrea energy only refers to fuelwood, charcoal, cow dung, agro-residues and kerosene. In rural areas, energy for agricultural purposes derives from human or animal power. Without access to services that modern energy could offer, the country will remain vulnerable and unable to create income, especially rural areas would be excluded from the developing process. This process does not evolve as a linear correspondence with energy, even if it remains an important factor. Desertification and drought affect the sustainability of the development through their relationship with the social dimension, in terms of poverty, poor health, malnutrition, lack of food security, as well as migration and other demographic dynamics as the rural-urban shift of the population. The rural communities have the urgent need to access the services that commercial energy provides and to do it in a way that respects environment, enhances the human capital and stimulates virtuous circle between productivity and income. The development and efficient use of various energy sources, in relation to local endowments, is a priority field for national action plans. In Eritrea, the aims are particularly focused on reduction of fossil fuel dependency [45].

There is a significant demand for clean energy, as 80% of energy needs are met by fuelwood and 88MW of electricity is generated from diesel/heavy oil fired plants. According to the World Bank’s, in 2014 Eritrean’s electrification rate was estimated at 30% and the access deficit at 3.2 million people, which is similar to the access deficit to non-solid fuel. The share of biomass in the total final energy consumption was estimated at 73% and primary energy intensity at only 12%. Statistical data are available until 2013 and they are shown in the following graphs.

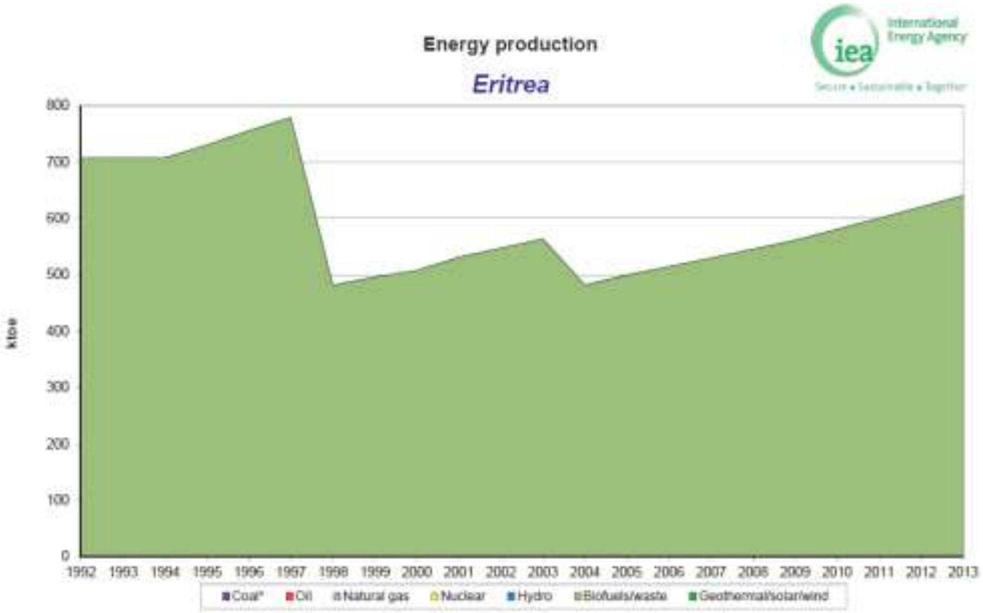


GRAPH 2 ERITREA TPES, YEARLY TREND

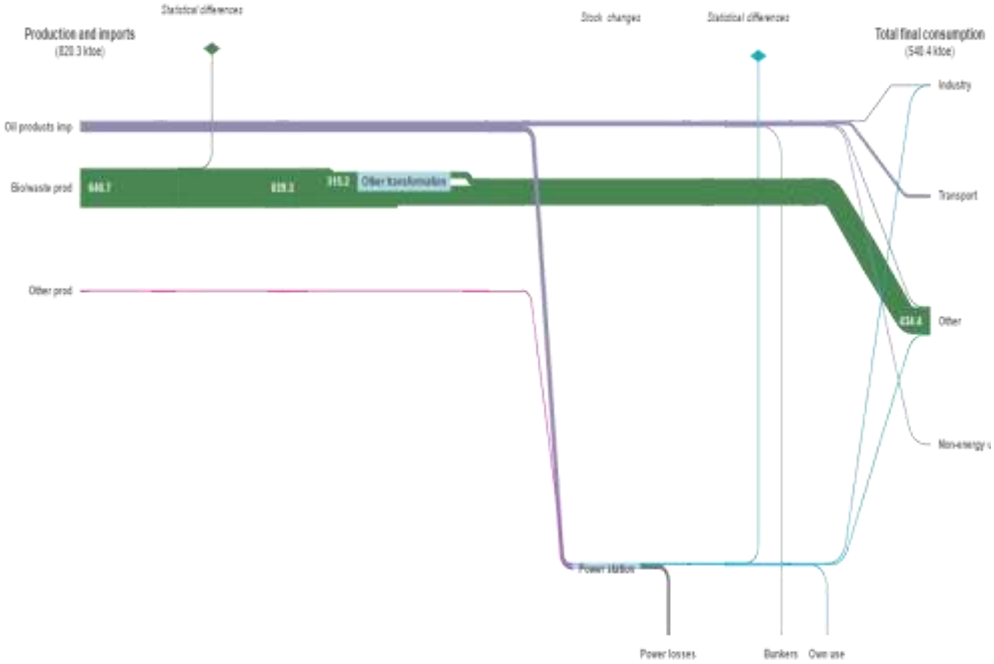


GRAPH 3 SHARE OF TOTAL PRIMARY ENERGY SUPPLY IN ERITREA (2013)

In Graph 2 and Graph 3, the share of TPES excludes electricity trade and peat and oil share are aggregated with coal, when relevant. The supply of energy is strongly unbalanced upon biofuels and waste, mainly consumed in residential sector, while oil is used in transport sector. It is clear that the production of energy is almost all related to traditional fuel, as reported in Graph 4 and the differences in consumprtion are shown in Graph 5 for the year 2013. Moreover, it is important to notice that the TPES in 2013 was around 819ktoe, but the total final consumption was only 540.5ktoe. There were significant losses in the conversion and transport processes.



GRAPH 4 ERITREA ENERGY PRODUCTION, YEARLY



GRAPH 5 ERITREA FINAL CONSUMPTION, BY FUEL AND BY SECTOR (2013)

The Government recognises that Eritrea’s current pattern of energy consumption is unsustainable. Expediting appropriate changes in the current energy-consumption pattern, increasing efficiency in the use of energy, and promoting energy conservation are matters of great urgency and, therefore, top priority of the Eritrean Government. With these purposes, the Government is committed to create a “policy and regulatory framework conducive to private investment in prospecting, exploration and development of hydrocarbon resources”; modernisation and expansion of the country's power generation system; exploration of potential for harnessing hydro, solar, wind power and biogas; to introduce a new energy pricing to facilitate the development of alternative energy sources, to promote cost-effective energy utilisation and conservation, and to protect the environment” [46].

4.1.3. Environmental context

Climate

Eritrea covers an area of $125700 km^2$ [46] and has a coastline of over $1000 km$. It is situated in the Horn of Africa, neighbouring Sudan, Ethiopia and Djibouti and bordered to the East by the Red Sea, between latitudes 12° 42’ N to 18° 2’ (Figure 26). The total cultivable area is estimated at around 11.6 million ha. The total cultivated area was 503 000 ha in 2002, only the 4% of the total area of the country; in 2012, the arable land is grown up to 6.8% of land area [47]. Arable land was 500000ha, while the area under permanent crops was 3000 ha. Most of the country consists of savannah, steppes and desert, particularly in the south-western lowlands and in the east near the Red Sea. The highlands, where altitudes range between 1500 and 2000m are among the oldest areas cultivated by humans and are showing signs of overuse. Eritrea’s physical features are characterised by *central and northern highlands* extending for about 350km north to south; *flat coasts* of the eastern lowlands; *flat plains* of western lowlands interspersed with hills. The altitude across the country varies considerably, from 1500 to 2400 meters above the sea level in the highland – the capital Asmara is 2300m asl – from 0 to 500 meters in the eastern lowland areas and from 700 to 1400 meters in the western lowlands [48].

The country is divided into six agro-ecological zones representing two different rainfall regimes –summer and winter [49]. The summer rains are brought by south-westerly monsoon winds and are concentrated mainly in the months of July and August. They affect mostly the central highland and the western lowland. The winter rains typically occur from November to March and are influenced by the north-easterly continental winds.

The zones are:

- Sub-humid
- Arid highland
- Moist highland
- Moist lowland
- Arid lowland
- Semi-desert

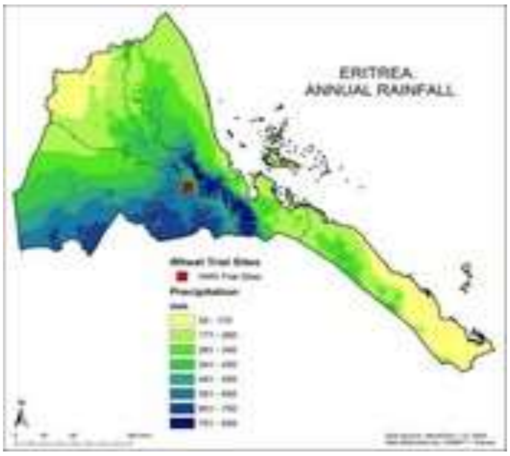


FIGURE 29 ERITREA ANNUAL RAINFALL

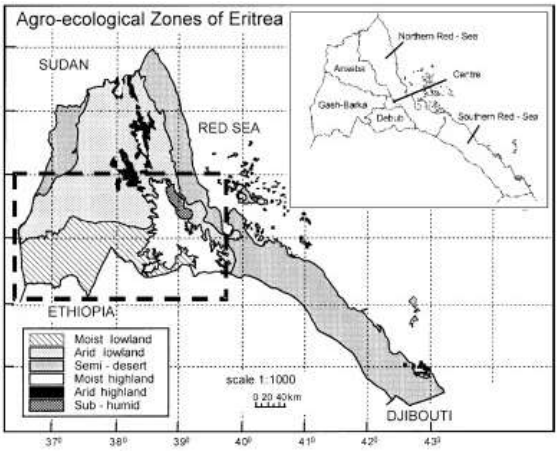


FIGURE 30 AGRO-ECOLOGICAL ZONES OF ERITREA

The zones are special classification of the landscape into areas with similar agricultural and ecological characteristics. They also exhibit comparable agro-climatic conditions for crop and livestock production. The agro-ecological zones, hence, represent Eritrea's comparable land resource condition, such as soil, water and vegetation parameters; moreover, Eritrea's similar land management conditions e.g. ruggedness of agricultural land, slope steepness [48].

Characteristics	Agro ecological zone					
	Sub-humid	Arid highland	Moist highland	Moist lowland	Arid lowland	Semi-desert
Area [km^2]	1006	3243	9302	20363	43115	48772
Total area (%)	1	3	7	16	34	39
Slope (%)	8-100	2-100	2-30	2-30	2-30	0-30
Altitude (asl)	600-2600	1600-2600	1600-3018	500-1600	400-1600	<100-1355
Rainfall (mm)	700-1100	200-500	500-700	500-800	200-500	<200
Temperature (°C)	16-27	15-21	15-21	21-28	21-29	24-32
PET (mm)	1600-2000	1600-1800	1600-1800	1800-2000	1800-2000	1800-2100
DLGP (days)	60-120	0-30	60-110	50-90	0-30	0
MLGP (days)	90-240	30-60	90-120	60-120	30-60	<30

TABLE 7 AGRO ECOLOGICAL CHARACTERISTICS - PET IS POTENTIAL EVAPO-TRANSPIRATION, DLGP ID DEPENDABLE LENGTH OF GROWING PERIOD, MLGP IS MEDIAN LENGTH OF GROWING PERIOD

1. Sub-humid zone: the sub-humid zone is located in the eastern green belt, it is the smallest area (only 1% of the total). Main crops cultivated are maize, sorghum, wheat, barley. There are also perennial tree as coffee and mango and vegetables for sale in local markets.
2. Arid highland: this agro ecological zone is an extension of the southern highlands, it is hilly and mountainous, which cause limited agricultural activities in valleys. Livestock is common, especially goats and cattle.
3. Moist highland: this is the most densely populated zone. Technological level is still low, as farmers use oxen to plough fields. Invasive plants as cactus are spread in the lands.
4. Moist lowland: it is located in the Southwestern lowlands, its slightly slope and the higher rainfall are in some cases sufficient for rain-fed production.
5. Arid lowland: crop production is mainly sorghum and millet, for their short-term growing cycle.
6. Semi-desert: it is the sandy coastal area. Because of high temperature, crop production is poor, except from few sparse irrigated areas. Higher relevance has fishery.

Average annual rainfall is about 380mm, varying from less than 50mm to over 1000mm. Over 90% of the total area receives less than 450mm and only 1% receives more than 650mm of annual rainfall. Rainfall in Eritrea is torrential, of high intensity, short duration, and varies greatly from year to year. The rainy season for the highlands and western region extends from June to September [45]. Because of the topographically ragged nature of the highlands, thin soil formations and a completely deforested terrain, most of the runoff turns into violent flash floods. Mean temperature varies between the agro-ecological zones, ranging from 18°C in the highlands to 35°C in the lowlands. Annual evapotranspiration rates range from 1900mm in the northern Red Sea coastal basin and plains, to 1700-2000mm in the northern highlands and 8000mm in the Gash-Barka basin.

The climate of about 70% of the country is arid with a mean annual temperature greater than 26°C. About 22% of the country enjoys a cool semi-arid climate. The area encompasses the high southern areas of the central highlands as well as the north. In this zone, the mean annual temperature is less than 19°C and the mean annual rainfall is between 400 and 600 mm. This climatic zone offers the best potential for expansion of rain-fed crop production. Over 65% of Eritrea's population lives in this area. Eritrea is vulnerable to climate change and both the marine and terrestrial ecosystems have been negatively affected. Over the past 60 years, temperatures have risen by approximately 1.7°C according to the Ministry of Land, Water and Environment [45]. Unfortunately, increased population pressures combined with a lack of appropriate land management has resulted in serious land degradation through soil erosion. Total population was almost 4.3 million in 2004 and it reaches more than 5 million in 2014, with a population growth rate of about 2% in years between 2002 and 2014 [50]. Demographic growth in Eritrea will be mostly from the resident population, but also from repatriated refugees. National population density reached 37inhabitants/km2 in 2004, but it was 51 in 2014 [50]. Improved water sources was available for less than 50% of the population in 2002, about 60% in 2014. Net primary school enrolment was 61% in 2005, but updated data are not available. About 7 out of 10 persons live below the minimum standard of living threshold and 66% of the population is estimated to be poor but again, no more recent data are available.

The process that affects Eritrea, causing rising temperatures and soil erosion, could be resumed through the term *desertification*:

" Desertification is the continuous and sustained decline in the amount and quality of the biological productivity of arid and semi-arid lands caused by inappropriate land-use practices, whether or not in conjunction with extreme natural event. Such stress, if continued over the long term, leads to ecological degradation and ultimately to desert-like conditions." [51].

Beside climatic conditions, generally due to geographical position, main causes are population pressures, improper systems of cultivation, improper irrigation systems, nutrient losses, soil erosion. The population growth and the associated demand for land have caused social and ecological imbalances that lead to reduction in land productivity. The vicious cycle starts with lower yields, that makes the land worked even more intensively, which is the cause of land degradation. Considering the system of cultivation, it has always been largely traditional, with poor crop management. All rain fed crops are local varieties and they are chosen by the farmers over generations, giving precedency to short growing crops. Fertilizers or other chemical treatments are seldom used. Weeding is done by hand, land preparation is carried out with traditional plough drawn by oxen or camels.

The irrigation is often seasonal and it means that is spate irrigation. Under this type of irrigation, rivers are diverted by temporary earth structures into fields. It is a low cost system, but it requires a high human labour. Only minimal water control is possible, hence frequent maintenance works are necessary because of flood damages and water management is not sustainable. If a farmer, indeed, extract a huge amount of water, the following one, using the same water source, could probably experience water scarcity because of the withdrawal of the previous farmer. On the other hand, perennial irrigation systems are mainly dependent upon surface and groundwater resources, but again, they are affected by exploitation or over-exploitation. If not adequately designed and managed, irrigated land is susceptible to flood damage in the case of spate irrigation, and it could cause groundwater resources depletion.

Another parameter that affects the desertification process is soil erosion. The phenomenon consists in detachment and transport of soil particles by water or wind. In Eritrea, water erosion is the dominant one in the Central Highland Zone, instead in the Coastal Plains Zone, erosion by wind is more common because soils are sandy and vegetation cover is sparse. Recently, soil erosion is becoming the most serious environmental problem threatening Eritrean agriculture. Natural factors such as abnormally intense rainfall, even if erratic, and rugged topography (especially in the Central Highlands Zone), combined with over-grazing and the massive destruction of the highland forests in the last few decades, have led to high rates of soil erosion. The loss of topsoil causes decline in crop productivity and land, which can degrade within a short period and may take several years to return to its original condition. That is one of the reasons, together with harvesting and retaining rainwater, to construct the massive terraces in the Central Highland Zones, where every mountain shows the typical feature in Figure 31.

The last factor is the nutrient losses through soil erosion and crop removal without replenishment by fertilizers – both natural and chemical. Farmers seldom use chemical fertilizers, and now animal dung is often used as energy source rather than being recycled in agriculture.

FIGURE 31 TERRACES IN ERITREA

Water resources

In order to face the challenge of water resources overexploitation, in collaboration with the UN, the government is constructing micro and check dams, as well as implementing tree planting and other sustainable environmental measures. A great example is the exploitation of the *fog-water* potential. Mostly in the eastern escarpment, there is fog occurrence during the winter period, some potential sites like Arberabue have an average of $8\frac{l}{day\cdot m^2}$ [49]. In this particular area, there is continual fog occurrence during the winter (from November to March). Fog-water is clean and safe for drinking since chemical and microbiological analysis meet the WHO potable water standards. It could be collected with a simple technology, such as large fog collectors (LFCs) connected to water reservoirs. The LFCs are big plastic mesh erected perpendicular to prevailing wind and installed at a higher elevation, preferably at the saddle of a mountain. The water droplets collect on the mesh during foggy conditions, and then fall into a gutter attached at the lower edge of the mesh. The fog-water flows by gravity to a sedimentation tank and to water reservoirs.

According to the 2006 development report of the UN, the minimum water threshold per person for a day is 20 litres, but still 1.1 billion people use only 5 litres per person a day while in developed countries the average is 200 litres in Europe and 400 litres in the United States.

Water infrastructures, that allow storing water, are the most important elements of any efficient water management. The alarming fact is that poorest countries in terms of ground water resource, such as Eritrea, are also much poorer in both catching and storing it.

In Eritrea, three main drainage systems can be distinguished:

- The Mereb-Gash and Tekeze-Setit River systems, draining into the Nile River;
- The eastern escarpment and the Barka-Anseba River systems, draining into the Red Sea;
- The river systems of a narrow strip of land along the south eastern border with Ethiopia, draining into the closed Danakil Basin.

Although no measurement of runoff is available, the internally produced renewable water resources are estimated at around $2.8\frac{km^3}{yr\cdot}$, most of which are located in the western part of the country. There is only one perennial river, the Setit River, which also forms the border with Ethiopia. All other rivers are seasonal and contain water only after rainfall and are dry for the rest of the year [11]. There are no natural fresh surface water bodies in the country. Artificially dammed water bodies are sparsely found in the highland parts of the country.

Groundwater can be tapped in all parts of the country but not in the quantities and of the qualities desired. Four hydro-geological units, based on the different geological units, recharge conditions and hydraulic characteristics, can be detailed [48]:

- Granular aquifers, which cover large areas in the western and eastern lowlands and along river valleys and flood plains. Unconsolidated aquifers consisting of the alluvial sediments are also found in the Asmara area where rainfalls are higher, Red Sea coastal plains and at the foot of fault scraps and mountains;
- Fissured and jointed volcanic aquifers, which are found in the central highland plateau southeast of Asmara and west of Assab, the Alid hot spring and in the southern part of the country;
- Fissured and karstic aquifers of consolidated sedimentary rocks, limestone, coral reefs, evaporate deposits and the marbles of metamorphic assemblages;
- Fissured aquifers of the basement rocks of crystalline metamorphic rocks and associated intrusive rocks, which are localized along weathered and fractured zones, with limited groundwater resources.

The WRD/UNICEF report of 2003 "Eritrea - Planning, management & advocacy tool for rural water resources development" mentions a goal of safe water sources coverage of 60% of the rural population by 2015. Unfortunately, data availability stops in 2008, but a remarkable increase could be noticed from early 1991. In that year, improved water resources access, limited to rural population, was 39%; in 2008 it was 57% [50].

The recent water point inventory counts 5365 water points. About 3374 are unprotected dug wells and 1233 are contaminated surface water points. Typical borehole depths are in the range of 20 to 70 m. Population has access to water by filling tanks and gericans (small tanks of 5-10 litres) directly from the water point (Figure 32). Deep aquifers are still not known although the nation is moving to a deeper investigation of interconnected issues about water resources. Problems of groundwater depletion have been reported in various parts of the country. Apparently, there are a few natural springs, but an inventory is not available. In this perspective, the United Nation Development Program "Strengthening capacity of the water resources department to plan, monitor and sustainably utilize the water resource" takes place. The purpose is to improve access to safe water supply, but it passes through capacity building in management and protection strategies.

FIGURE 32 WATER POINT IN MAY HABAR

Despite Eritrea's heavy reliance on surface and ground water resources for most socioeconomic sectors, knowledge base of water resources is limited to serve as inputs for sustainable management of the water resources. Apart from the 1998 limited scope sector study on 'National Water Resources and Irrigation potential Project' no large scale water resources potential related assessment has ever been undertaken at a national level [11]. Besides the lack of full information on ground water and surface water potentials, the risk of mismanagement is further magnified with the lack of any institutionalised regular quantitative and qualitative monitoring system in place.

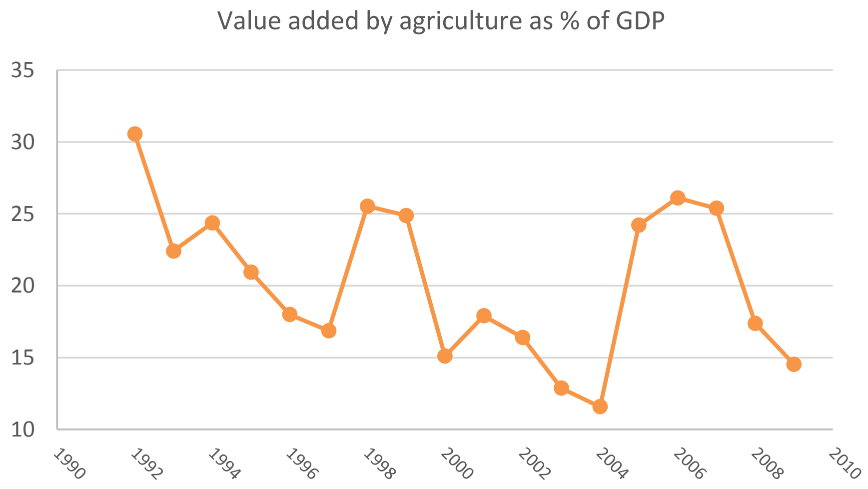
The ancient method used to collect water is building cisterns, originally introduced by Italians to supply water for the steam driven locomotives. Recently, the roof catchment technique was adopted in those zones which can benefit from the method, hence excluding the coastal area. The most applicable types of roof catchment are the ones that permit a good water quality, as galvanised corrugated iron sheet or corrugated plastic and smoothened tiles. When unavailable, cement or even palm or hey could be used.

The real innovation linked to governmental interest about resource management, arrived in 1991, when the first Green Club was born in the country. The aim of the club was to promote for natural resources

management, in a comprehensive vision that connects farmer needs and natural constraints. The greening campaign is focused on soil and water conservation, involving communities and students that participates during their summer breaks. The main point beside planting new trees, is the construction of dams and ponds to preserve water from flooding, to ensure self-reliant development in livestock and agriculture.
Currently there are about 187 dams with a capacity of over 50000 m3 each. About 42% are for municipal use and irrigation, 40% for municipalities only, 13%for irrigation, and 5% are not used. The total capacity reaches 94 million m^3. Other sources tells about $411000m^3$ check dams, and 108000 micro-basins [52].

4.1.4. Economy and policy context

Eritrea's economy in general and the agricultural sector in particular were seriously affected by the combination of war, recurrent droughts and degraded lands. Agriculture, which is based on smallholder farming, and its contribution to Gross Domestic Product (GDP), continue to show a fluctuating trend over the years (Graph 6). Up to 70% of the population depends on farming and fishering for their livelihoods, but although the majority of the population still rely on these activities for their survival, the sector only accounts for about 16.9% of GDP and about 20-30% of commodity exports, according to Agriculture Sector Strategy (2014). This low contribution to GDP and exports is caused by highly variable climatic conditions, inefficient traditional farming methods, limited resource allocation, and low profit margins. Moreover, private-sector activity, dominated by trade and services, remains weak, and access to hard currency is one of the major constraints. The fact that over 80% of the poor live in rural areas and depends on agriculture suggests that increasing agricultural production and productivity would have a remarkable impact on poverty. For this to happen, modernising the sector is required, shifting away from the current farming systems and crops to semi-commercial and peri-urban agriculture; small-scale irrigated horticulture, commercial farming, and agro-pastoral spate irrigation systems based on flash flooding (also named "spates").



Graph 6 Agriculture, value added (% of GDP)

Nevertheless, Eritrea is aiming at creating a modern, private sector-led economy, according to its *National Indicative Development Plan 2014-2018* [3]. Attaining this objective is driven by the growing mining sector, but on the other side is compromised by an inadequately enabling investment and business environment, United Nations sanctions, and overall weak macroeconomic conditions. Real GDP growth was projected to increase from 2.0% in 2014 to 2.1% in 2015, double the rate recorded in 2013, because of increasing investments in the mining sector. Over the medium term, the government sees further prospects in improved trade with Middle-Eastern and Asian countries, additional mining activities, the growth of the food sector and the development of the tourist industry. The latest available GDP composition (2015) is: services (59.9%), non-manufacturing (17.3%), agriculture, hunting, forestry and fisheries (16.9%) and industry (5.9%) [3].

The government has given priority to three pillars in the Development Plan: human resource development, infrastructure development and food security. There have already been targeted public investment programmes in education and skills development and in agricultural production and productivity improvement. In seeking food security, the institutions are addressing social needs and are rehabilitating existing infrastructures. Progress has been made in eliminating many restrictive policies, laying emphasis on creating favourable conditions to private sector growth. However, the private sector remains small and underdeveloped. Progress in the privatisation of some state-owned enterprises, announced in 2012, has been slow, limiting the inflow of private capital beyond the mining sector. The offer of shares in the Eritrean Telecommunications Corporation (EriTel), the National Insurance Corporation of Eritrea (NICE) and the Asmara Brewery to domestic investors has not created a visible impact in the economy, services are even poorer than before. Improvement in the overall implementation of the privatisation process will require addressing deficiencies in energy, communication and property rights.

In early 2013, the government relaxed some foreign-exchange transactions and took modest steps towards liberalising the economy. The reason was that, previously, strict control and reduction of remittances resulted in an overvalued Nakfa (national currency) and growing parallel market. Inflation declined slightly in 2014 because of food-supply shocks, high foreign exchange demand, and high commodities prices on the international market. Lower international food prices and weaker oil prices in 2015 and 2016 should contain inflation at an annual average of about 12% for the same period.

Policies on natural resources management and environment

Inside the country, a number of sectorial legal frameworks for natural resource and environmental management exist, including not only water, but also land, forestry, fisheries. The current threat of the growing mining sector addresses interest towards natural resources conservation. Water deficiency is overrun by inefficient use and mismanagement of the resource, due to a number of linked factors such as social awareness, lack of infrastructures and poor sectoral capacity about land use systems. Actually, there is no legislation, but an ”Environment Proclamation” is being developed. Institutions were included in the development of the project and the practical case, in order to understand the context, the activities that regulate natural resources in rural areas, the future plan elaborated by government.

The institutions involved in water resources management are:

- The Ministry of Land, Water and Environment (MoLWE) with the Water Resources Department (WRD), which has the followings functions according to the Draft Water Law (1997): assess and evaluate the water resources’ potential of the country; function as a resource centre for water-related data/information; manage and develop national water resources; evaluate, monitor and supervise all water-related studies, development projects and programmes of national interest; grant, manage and inspect the implementation of water permits and waste discharge permits.

  The Ministry’s mandate further includes legislation, and establishing a system of water rights and obligations. The WRD is split into two divisions according to these two different tasks: Water Resources Management and Use Division and the Water Resources Assessment Division. As regards water supply, the WRD initially served the entire country, even including maintenance and repair of equipment, but services have been decentralised since 1996. The problem is that the regional authorities, which are now responsible for the implementation and maintenance of rural water supply projects, do not have the capacity to effectively take over this responsibility and several units of the WRD are therefore still involved in local project implementation.
- The Ministry of Agriculture (MoA) and its Soil Conservation and Irrigation Development Unit, which is part of its Department of Land Resources and Crop Development;
- The Ministry of Local Government (MoLG), responsible for the Regional Administrations;
- The Ministry of Health (drinking water supply);
- The Ministry of Transport and Communication, through its mandate for meteorological data collection.

The government of Eritrea has addressed great efforts to wisely manage the precarious state of the environment, as the National Soil Conservation Program. Under this program, a total ban on cutting live trees, hunting and charcoal making was introduced and still in force [53].

In a continental vision, Eritrea is part of the Council of Ministers of Water Affairs of the Nile Basin States (Nile-COM) as an observer, together with Burundi, the Democratic Republic of the Congo, Egypt, Ethiopia, Kenya, Rwanda, Sudan, the United Republic of Tanzania and Uganda. It is a prospective member of the Nile Basin Initiative (NBI). NBI provides riparian countries with the only all- inclusive regional platform for multi stakeholder dialogue, information sharing as well as joint planning and management of water and related resources in the Nile Basin. The other international issues that involve Eritrea are those about the Setit and Mereb-Gash rivers, shared with Ethiopia.

Eritrea was the last African country to gain independence and, although war has been deteriorating for the nation, it is and always have been a very proud country. The government has always made resistance to international aid, and so did population, mostly because of their willingness to finally administer their own territory. In keeping in line with its self-reliance policy, the Government of Eritrea stopped requesting financial assistance from the United States in 2005, and fully cut off all third party NGO's that were financially sponsored by the U.S. after 2006. The government believes foreign assistance breeds a culture of dependency that shackles African countries into a perpetual cycle of poverty.

4.2. **The Ferrando Ezechiele Agricultural Estate**

In this section of Chapter 4, the farm subjected to analysis is described in terms of activities, geography, and current situation. Analyses of actual energy consumption are carried out through a micro grid software simulation tool, HOMER Pro® by HOMER Energy. Then, the design of the energy system for the irrigation purpose is made in a demand-driven design approach, evaluating the load curve through a survey filled by farmers. The last step is to consider another designing method, a comprehensive design of the irrigation and the energy systems, one depending on the other. With the purpose to find the real water request of the crops cultivated, CROPWAT is used, inserting local data about the affecting parameters. The possible irrigation techniques are studied in relation to physical constraints and characteristics of the territory, looking for the solution that could save as much water as possible. The energy required to supply that amount of water is evaluated in a way that fits the best the real needs of the farm. The paragraphs show also how to collect data and how to use them to evaluate the water and energy request of the farm. The three design approaches are compared in terms of energy consumption and the ways to supply that quantity of energy are investigated in relation to local resources. Moreover, inside the integrated approach of load calculation, considering different irrigation techniques in relation to the context, various solutions are simulated to obtain economic comparisons, with the purpose to identify the solution that fits the best the farm needs, taking into account resources constraints.

4.2.1. Location, activities, current situation

FIGURE 33 THE FERRANDO EZECHIELE AGRICULTURAL ESTATE

The practical case refers to a private estate near Mai Habar, in Northern Red Sea region, the Ferrando Ezechiele Agricultural Estate. The estate has been conducted for more than thirty years by Mr Ferrando and now, it is managed by his wife Midò Andu and one of their daughters.
The site is along the street that connects Nefasit to Dekamhare, at the 13th km. The villages in the area are mostly based on agriculture and small livestock activities, frequently Araldo, Arebi cattle, Barka camels and goats, beside chickens. The nearest village is Mai Habar, which is connected to the national electric grid and has a communal water point for the population. The electricity supply is guaranteed by the Herghigo power plant, but the production is unreliable and the supply suffers frequently non-programmed black outs.
During last years, the region has suffered frequent droughts that made the field yield decrease drastically. Due to water scarcity and, above all, due to a wrong management of common resources like soil and water from local population, the productivity of the farm has dropped to low level. In this region, the desertification process is accelerated mostly due to the high dependency on fuelwood as the main source of energy for households.
During the round trip to the farm, the information necessary to estimate the current irrigation practice and the current energy load request were collected. In Figure 34, the farm boundaries are reported and the red points refer to the existing wells.

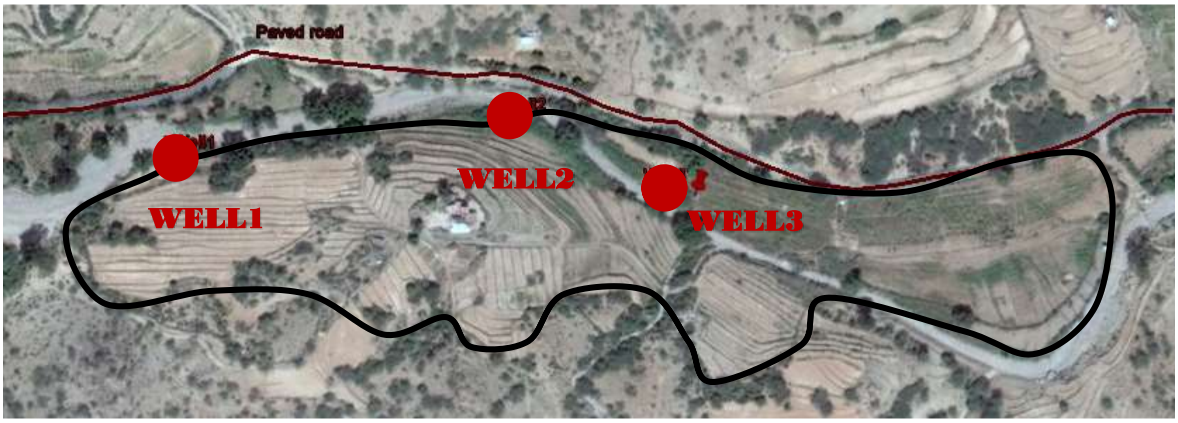


FIGURE 34 THE FERRANDO EZECHIELE AGRICULTURAL ESTATE

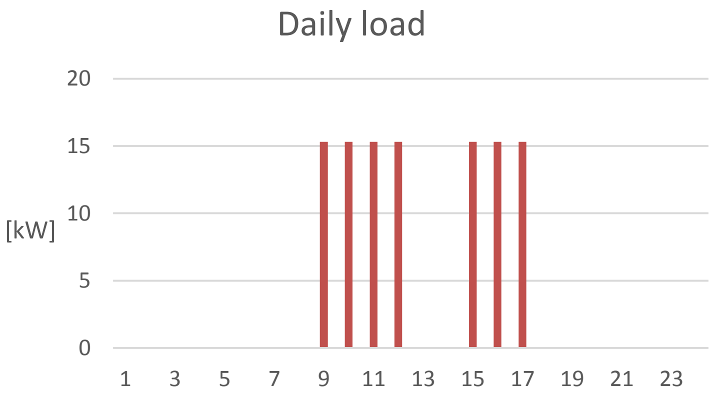
To understand the actual energy consumption, the load curve is evaluated through direct observation and a survey filled by farmers. Each well has a diesel motor pump and they are used to directly irrigate fields. The nominal power of the pumps are summarised below.

Well 1 (Zone 1)	4.4 kW
Well 2 (Zone 2)	4.4 kW
Well 3 (Zone 3)	6.5 kW

TABLE 8 MOTOR PUMPS NOMINAL POWER

Water is pumped to two water tanks of 5m^3 and from the reservoirs, it flows to the fields by gravity. The process is continuous and it lasts for about 7 hours per day, only during the irrigation days. During the rainy season, irrigation actions take place every 6 days, while during the non-rainy season two following actions happen every 3 days. This configuration does not supply water to the entire surface of the farm, but only to around one half of the area, since water shortages are frequent.

To have an idea of what is the current expense of the irrigation and energy system, an energy simulation program is used, HOMER Pro. The daily load curve is calculated through information collected from farmers and it is inserted in HOMER Pro, together with information on energy resources used, resumed in the tables below.



GRAPH 7 CURRENT DAILY LOAD

The only energy source used in the irrigation system is diesel to fuel the motor pumps. Through a governmental subsidy, farmers can have a certain amount of fuel per month at a reduced price depending on the farm size and its products. The price is fixed and it is advantageous for farmers because diesel market price in Eritrea could be fluctuating, depending on international trade.

In HOMER Pro the required parameters about diesel are inserted, considering an initial investment equal to zero because the motors already exists; a replacement cost estimated by [54]; a lifetime reduced because of the motors age; an operation and maintenance cost higher than the normal one, because the efficiency of these motors is very low.

Capital cost [$]	0
Replacement cost [$/kW]	350
O&M [$/h]	1
Lifetime [h]	7000

TABLE 9 GENERATOR HOMER INPUTS

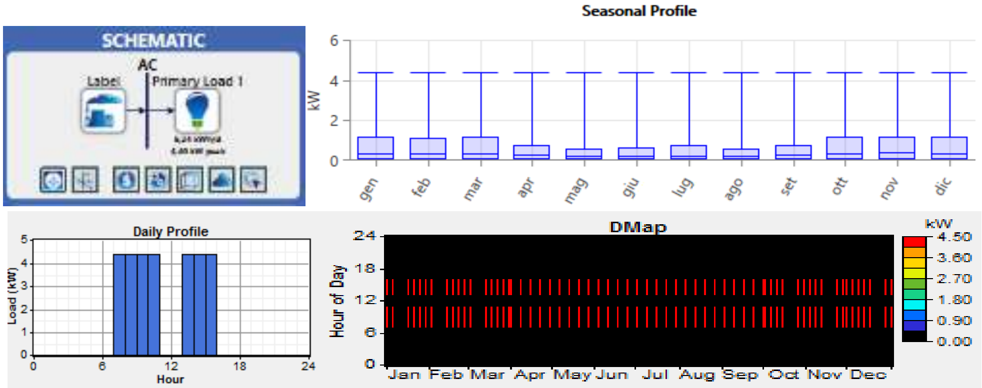


FIGURE 35 CURRENT ENERGY LOAD CURVE ZONE 1

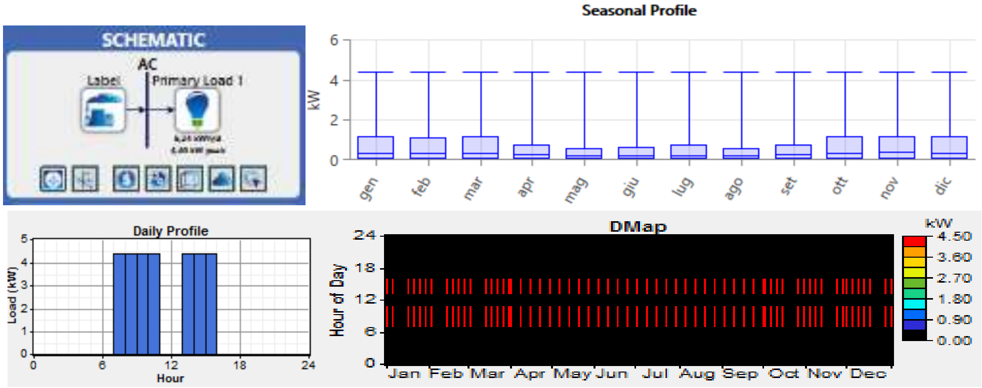


FIGURE 36 CURRENT ENERGY LOAD CURVE ZONE 2

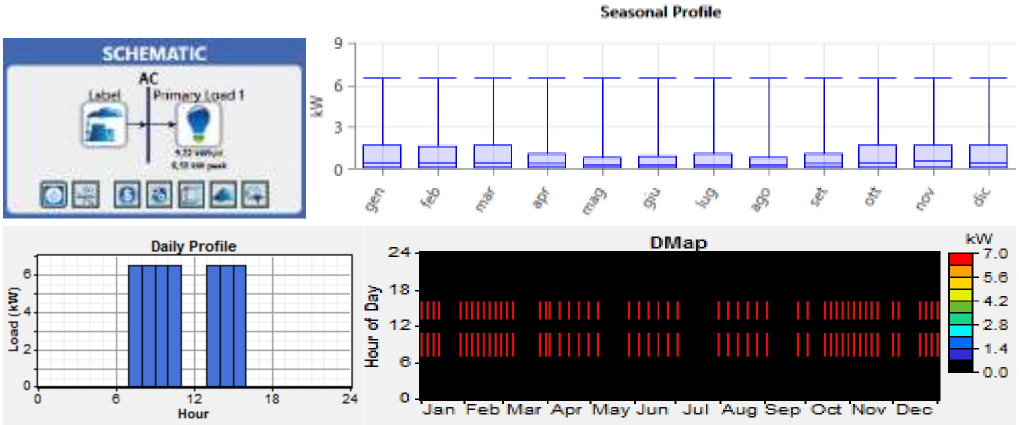


FIGURE 37 CURRENT ENERGY LOAD CURVE ZONE 3

4.2.2. Demand-driven design of the energy system

The second approach is used to evaluate a possible enhancement intervention, using a demand-driven design method. Having the load curve elaborated with farmers, HOMER Pro is used to find a new energy configuration able to meet the needs of the pumping and distribution system. No emphasis is given to the water needs assessment, because energy and water are not considered together.

The farmers did not want to change the shape of the load profile because during the central hours of the day, from 12 to 14, activities are suspended due to high temperatures. For these reasons, the load request for an irrigation day remains distributed as it was at the beginning, 4 hours in the morning and 3 hours in the afternoon. The energy load curves obtained are the following, divided in three systems because of the possibility to install a solar pump in each zone, with dedicated solar panels. Nevertheless, a unique energy system is also evaluated for a configuration with one energy production plant and three irrigation pumps.

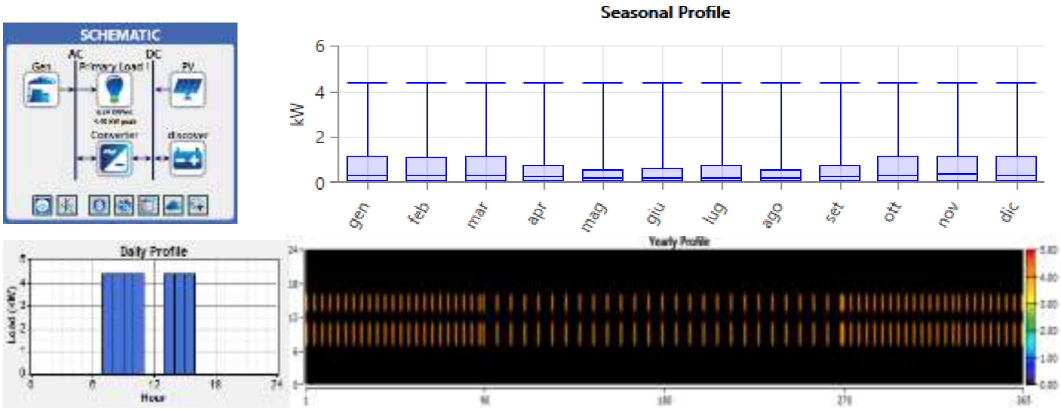


FIGURE 38 DEMAND-DRIVEN DESIGN - ENERGY LOAD CURVE ZONE 1

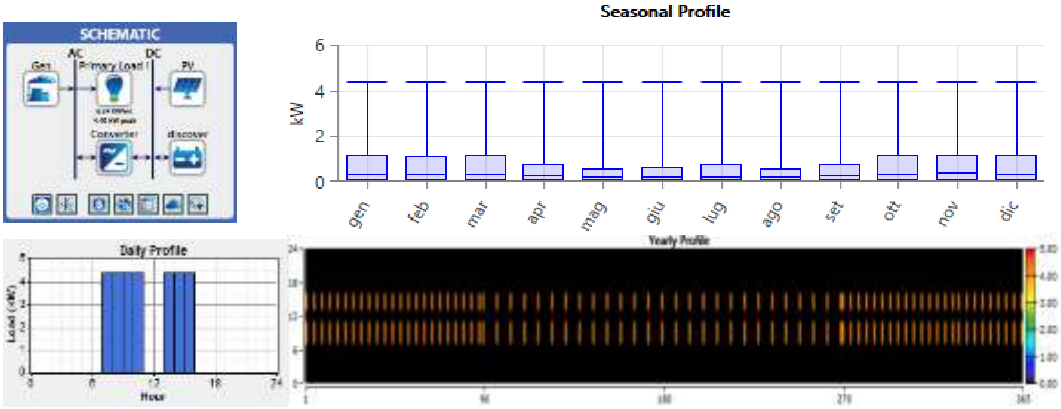


FIGURE 39 DEMAND-DRIVEN DESIGN - ENERGY LOAD CURVE ZONE 2

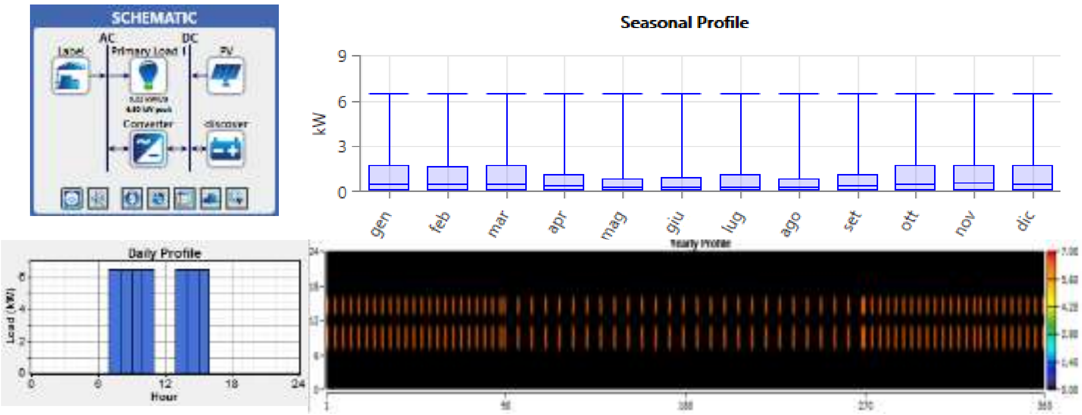


FIGURE 40 DEMAND-DRIVEN DESIGN - ENERGY LOAD CURVE ZONE 3

The energy sources to supply energy to the pumps are different from the previous approach ("current situation"). Considering the available renewable sources, simulations through HOMER Pro are carried out testing hybrid system or completely renewable systems. In the following pages the renewable energy sources assessment is reported.

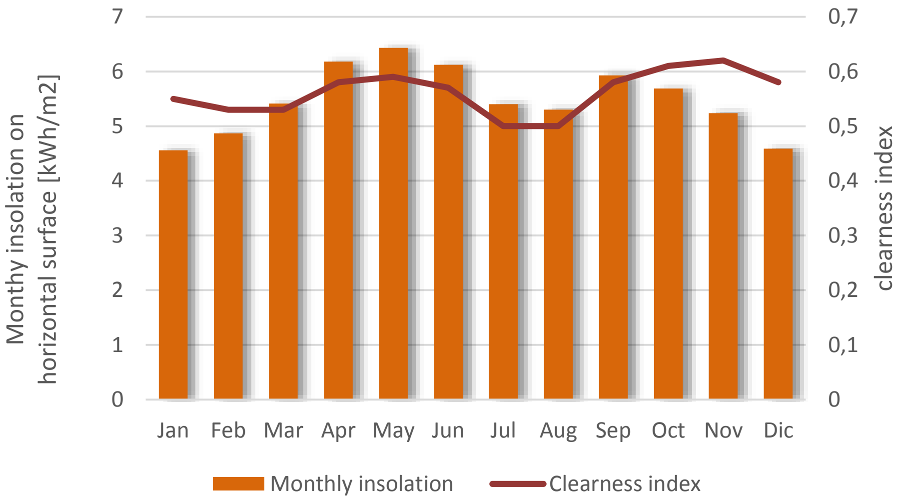
Energy Sources

SOLAR RESOURCE

Solar resource is synthetized by two quantities, the global horizontal solar irradiation in [kWh/m^2/day] and the clearness index [-]. The first one is the sum of direct radiation coming from the sun (*beam component*) and the amount coming from all the surroundings, sky and ground reflected (*diffuse component*). The clearness index is the measure of the clearness of the atmosphere. Mathematically, it is the ratio between solar radiation reaching the Earth's surface and the radiation that arrives at the top of the atmosphere. In clear sky conditions, the clearness index has a high value, tending to unit value; vice versa, in cloudy days, the clearness index tends to zero. The values are collected from online databases, in particular from the NASA resource website [55]. The values result from an average of at least ten years and they are specific for the location inserted in the website through longitude and latitude.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual average
4.56	4.87	5.41	6.18	6.43	6.12	5.40	5.30	5.93	5.69	5.24	4.59	5.47

TABLE 10 MONTHLY INSOLATION INCIDENT ON A HORIZONTAL SURFACE [KWH/M2] [55]

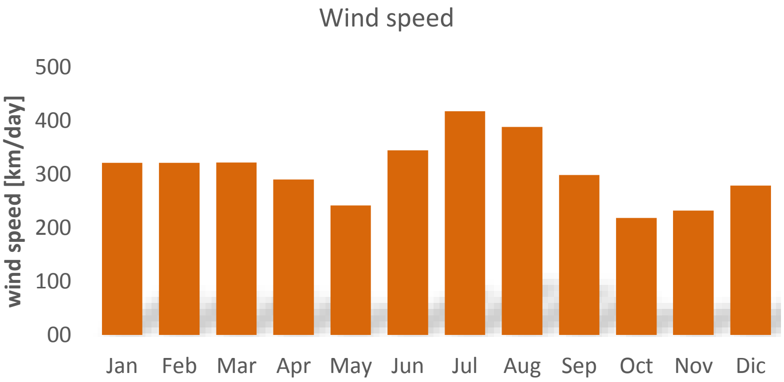


GRAPH 8 MONTHLY INSOLATION ON HORIZONTAL AND CLEARNESS INDEX

From the Graph 8 it should be noticed that during the rainy season that goes from May to September the clearness index decreases, as it does the solar radiation. On the other hand, the values of solar radiation still remain high and the solar needs derived from irrigation needs could be lower because of the more frequent precipitations.

WIND RESOURCE

The same resource website [55] used for solar data is used for wind speed data. They are available at different heights and the user should choose the best vegetation and surface type. The choice for the analysed farm was 20m and a “broadleaf trees (30% of coverage) and ground cover”. This choice should consider both the mango trees, that cover a large part of the land, and the generic crops planted during the year (ground cover). The average is 3.55m/s and the profile presents great variability between the months. The values are reported in km/day because this is the unit required by the computer program that analyses them.



GRAPH 9 AVERAGE WIND SPEED

Nevertheless, experts from the Ministry of Land Water and Environment of Eritrean government did not suggested to exploit the wind potential due to high gust peak in the region. Undertaking this parameter could be dangerous and even if specific data are not available, the installation of a micro or mini wind turbine was excluded by the analysis.

BIOMASS RESOURCE

At the moment of the visit, there were two oxen in the farm. Oxen are used only during the planting season, to plough fields in the traditional way and then they are sold. The biomass obtainable is already used as a natural fertilizer, as the animal biomass coming from the approximately forty chickens of the farm. Animal biomass for energy purpose should be avoided from energy analysis because of the poor availability of the source.

Considering the vegetal biomass, it is not appreciable in terms of quantity because in the area of interest the crops are chosen in connection with their water requirements, the yield, but also with the residual they generate: the less it is, the better is the crop. The agricultural residual is seen as a damage because it requires energy and water to be produced and it gives no revenues, it is to all intents a waste. As for animal dung, the poor residuals derived from agriculture, are used as fertilizers but also as primary energy, as it happens for dried plants used as fuelwood. Traditional biomass is used for cooking typical foods of the region, even if chopping wood is prohibited by law due to the strong deforestation Eritrea is suffering.

HYDRO POWER RESOURCE

hydro power resource is not considered due to high uncertainty of the river flow during the year. Moreover, when water is largely available, it is used for agricultural purpose and basic needs. Hydro power is not a feasible solution, nor in this specific period nor in the next future.

In order to understand how the software tool HOMER Pro carries out simulations, some information are provided about the calculation phases and about economical aspects. The components inserted in HOMER Pro are PV panels, converter, batteries and a diesel generator.

Photovoltaic power is modelled as a device that generates direct current, in relation to the solar radiation incident upon its surface. The power produced is:

$$\mathrm{P_{PV}} = \mathrm{f_{PV} Y_{PV}} \frac{\mathrm{I_T}}{\mathrm{I_S}}$$

Where: $\mathrm{f_{PV}}$ is the derating factor
$\mathrm{Y_{PV}}$ is the rated capacity of the PV array [kW]
$\mathrm{I_T}$ is the global solar radiation $\left[\frac{kW}{m^2}\right]$
$\mathrm{I_S}$ is the standard radiation, equal to $1 \left[\frac{kW}{m^2}\right]$

The derating factor takes into account the decrease in performance due to effects of dust on the panels, wire losses, elevated temperature or other factors that would cause the real output of the PV to deviate from the ideal one. It was decremented to 80% to consider the high temperature of the region of interest and the effect of dust.

To describe the cost of the PV array, the parameters to be specified are its initial capital cost, replacement cost, and operating and maintenance (O&M) cost per year. The replacement cost is the cost of replacing the PV array at the end of its useful lifetime, which is counted in years. By default, the replacement cost is equal to the capital cost and they are collected in a scientific paper about a project in Ethiopia, assuming that costs could be similar in Eritrea [54]. In HOMER Pro, the solar panel is modelled as a generic flat plate, without concentration because of the simplicity of this type of device. Moreover, a slope value of 15° was set and azimuth value of 0° because if the panel has around the slope of its latitude, it collects the maximum radiation it could. The ground reflectance is 20%, the standard value for agricultural land.

Lifetime	25 years
Derating factor	80%
Ground reflectance	20%
Slope	15°
Azimuth	0°
Capital cost	2000 $/kW
O&M cost	25 $/year
replacement cost	2000 $/kW

TABLE 11 INPUT FOR SOLAR PV

The battery is modelled in HOMER Pro is a device able to store a certain amount of energy. The battery has a fixed round-trip energy efficiency, which limits its velocity both in charging and in discharging phase, in order to avoid damages and not to reduce its lifespan. The properties of the battery are assumed constant and they do not vary with temperature: they are nominal voltage, capacity curve, minimum state of charge, round-trip efficiency. There is one more property, lifetime curve that shows the number of charge-discharge cycles the battery can withstand in relation to the cycle depth. The capacity curve relates the discharge capacity of the battery in Ampere-hours versus the discharge current in Ampere. Capacity typically decreases with increasing discharge current.

The battery chosen was Discover 12VRE3000TF-L lead acid battery with a nominal voltage of 12V, nominal capacity of 215Ah, round-trip efficiency of 85%. Lead-acid are suitable for solar PV application because of their high round-trip efficiency and for the cost-price ratio. Moreover, lead acid are more available on the market. According to the voltage range of the converter, the batteries per string were limited to one or two, while the number of parallel strings depends on the energy load and it is calculated by HOMER Pro.

Nominal voltage (V)	12
Nominal capacity (Ah)	215
Round trip efficiency (%)	85
Max batteries per string	4
Maximum capacity (Ah)	244.971
Initial state of charge (%)	100
Minimum state of charge (%)	20
Lifetime throughput (kWh)	3550
Capital cost ($)	240
O&M cost ($/yr)	10
Replacement cost ($)	150

TABLE 12 INPUT PARAMETERS FOR BATTERIES

The physical properties of the converter, such as the converter rectification and inversion efficiencies are assumed to be constant. The other parameters to be inserted in HOMER Pro are once again the investment cost, replacement cost, O&M costs. They are deduced from the scientific paper [54] and from standard data of the computer program.

Input	Value
Lifetime (years)	15
Inverter efficiency (%)	90
Rectifier efficiency (%)	85
Relative rectifier capacity (%)	100
Capital cost (€)	700 $/kW
O&M cost (€/yr)	10 $/year
Replacement cost (€)	700 $/kW

TABLE 13 INPUT PARAMETERS FOR CONVERTER

Last component is the diesel generator, not the same one of the current situation simulation. In HOMER Pro, a generator is a device that consumes fuel to produce electric and eventually thermal energy. Generators can be dispatched, meaning the system can turn them on only if necessary. Input parameters are economical ones and fuel type with its cost per litre. Moreover, the minimum and maximum electrical output could be specified, to avoid low efficient working conditions.

Lifetime (operating hours)	15000
Minimum load ratio (%)	30
Fuel type	Diesel
Fuel cost ($/hr)	0.6
Capital cost ($/kW)	300
Replacement ($)	300

TABLE 14 INPUT PARAMETERS FOR GENERATOR

Moreover, HOMER Pro requires general parameters for the project.

Annual nominal interest rate (%)	6
Expected inflation rate (%)	2
Project lifetime (years)	25
Goal	Economic minimization
Maximum annual capacity shortage (%)	20

TABLE 15 GENERAL INPUT FOR PROJECT SET UP

4.2.3. Managing the nexus in an integrated water-energy system design approach

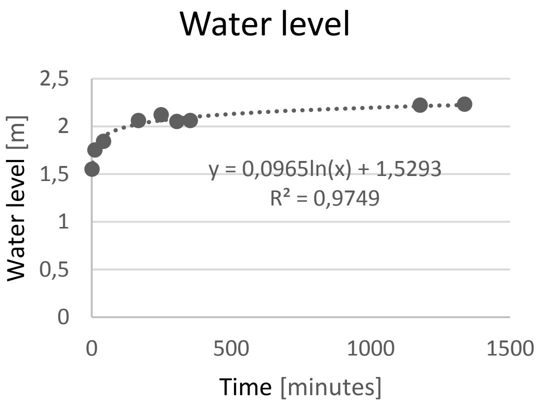
The WEF nexus and the relationship through crops cultivation, irrigation efficiencies and energy needs are locally investigated. Research on local water resources and possible water consumption rate (step 1) is carried out to understand the context and its constraints. Calculating water needs of agricultural products (step 2) leads to find the effective quantity of water that needs to be supplied to crops. Choosing different irrigation techniques (step 3) helps to evaluate differences in water waste among the various methods. Energy consumption is evaluated through the calculation of a new load profile that matches the real needs of the farm (step 4) and a possible energy plant is suggested.

Local water resources

The farm has three different wells, placed next to the river Mai Ainis, a seasonal river as shown in Figure 34. The wells are used whenever water does not flow into the river due to seasonal variability. During the hot period, the river is dry, while during the rainy season, floods are frequent. Water, when available, is diverted through a lined canal that crosses the whole farm, hence the irrigation in the region is a community system (see paragraph 2.3.2). The canal has openings every 15m to let water flow into the fields.

Water availability along the months should be known by historical measurements, but no measurements were available. Farmers rely on their past experience and, if the year is particularly dry, they reduce the production and turn it in subsistence agriculture. The round trip was in September, at the end of the rainy season, but unfortunately, year 2015 was one of the exceptional dry years. The river was really poor in terms of flowrate and when rainfall did arrive, it was thunderstorm, causing floods and damages not only to crops and fields, but also to wells and their structures. When a flood is intensive, water together with debris and woods may block the well. When this happens, the open well has to be emptied by the mud and now, this work is done by hand. It usually takes about three days to empty a well as the ones in the Ferrando Ezechiele farm, the workers go down in the well and collect the mud through simple tools like buckets. Then, through a pulley operated manually, buckets are brought out from the well. During the on field experience, three workers were committed to well number1 (Figure 34). Later, the well was closed in prevision of the dry season, to let the water be restored.

To have an estimation of the water endowment of the farm, documents or studies were searched in governmental archives. The Ministry of Land, Water and Environment was involved, in particular the Water Division. Mr Mebrahtu Iyassu, director of the Division, offered his collaboration and two consultants of his team came to the farm to do a simple pump test. The test was not complete because of the drought, which would alter the results of a full test. Thanks to their professional support, one well, the richest in water, was completely emptied and subsequently the time to refill the well to its original level was measured. Measurements were frequent at the beginning as water rapidly came into the well because of the high gradient of pressure, and they became less frequent as time went by.



GRAPH 10 WATER LEVEL WELL3

For well 1, it was not possible due to its damages caused by the flood. For well 2, it was only possible to measure its water quality, used in the following paragraph. Nevertheless, in order to take into account water shortages or water scarcity, some prevention measures were considered during the assessment. For instance, at the beginning, the crop pattern description included all the crops cultivated in the farm and they were all included in calculations of water and energy needs. Later, some of them were excluded, the most water intensive ones, because of their high water consumption. Furthermore, while initially calculations were made without considering water stress for plants, subsequently the assumption was relaxed for some more resistant crops, as maize and millet. This was done to take into account in a qualitative way the problem of water scarcity.

FIGURE 41 MEASUREMENTS ON WELL 3

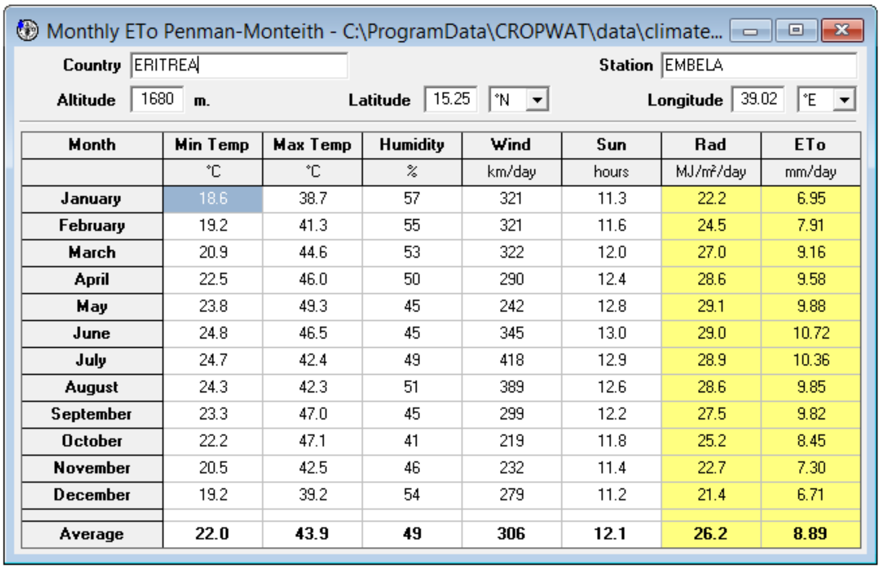
FIGURE 42 MEASUREMENTS ON WELL 2

Water needs of local products

In order to calculate real water needs of the existing crops in the farm, the net Crop Water Requirement (CWR) for each crop should be obtained. In this section, data requested to find water needs of the crops of the farm are resumed and the collection phase is explained. When there is a problem of data missing, the assumptions used to evaluate the information are listed. To calculate the water requirement the software tool CROPWAT is used, and all the input parameters are inserted in its modules. The result is the calculation of the *net* water requirement for each crop evaluated, in relation to the cultivated area. In next section, named “Irrigation techniques applied”, the results found through CROPWAT are manipulated to obtain the *gross irrigation requirements* (flowrate to be distributed) that gives the energy load curve.

- Climate module

The required data about climate were found thanks to the NASA Surface Meteorology and Solar Energy website [55], given the precise location of the estate available on google maps. The coordinate of the location are 15°15’11.87’’N 39° 02’ 11.50’’E elevation 1680m. It belongs to the agro-ecological class “moist highland” and it covers a total area of around 10ha. A check was made with other online databases for mean temperatures and relative humidity, such as [56]. Wind speed values were chosen from the same website in correspondence to the voice “broadleaf trees (30%) & groundcover” to simulate the current ground profile – the broadleaf trees might be the fruit trees and cereals and groundcover might be vegetables and small crops. In this section, the reference evapotranspiration is calculated by the software, listing its values as shown in Figure 43.


Monthly ETo Penman-Monteith - C:\ProgramData\CROPWAT\data\climate...

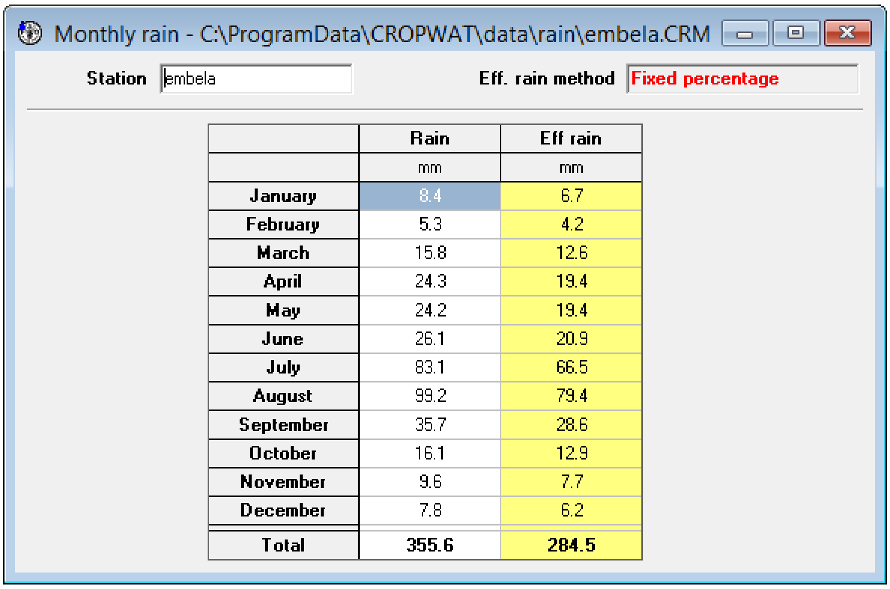
Country ERITREA
Station EMBELA
Altitude 1680 m.
Latitude 15.25 °N
Longitude 39.02 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	18.6	38.7	57	321	11.3	22.2	6.95
February	19.2	41.3	55	321	11.6	24.5	7.91
March	20.9	44.6	53	322	12.0	27.0	9.16
April	22.5	46.0	50	290	12.4	28.6	9.58
May	23.8	49.3	45	242	12.8	29.1	9.88
June	24.8	46.5	45	345	13.0	29.0	10.72
July	24.7	42.4	49	418	12.9	28.9	10.36
August	24.3	42.3	51	389	12.6	28.6	9.85
September	23.3	47.0	45	299	12.2	27.5	9.82
October	22.2	47.1	41	219	11.8	25.2	8.45
November	20.5	42.5	46	232	11.4	22.7	7.30
December	19.2	39.2	54	279	11.2	21.4	6.71
Average	**22.0**	**43.9**	**49**	**306**	**12.1**	**26.2**	**8.89**

FIGURE 43 CLIMATE MODULE

- Rainfall module

The monthly averaged precipitations derive from a 22-years average. Data were collected from the NASA Surface Meteorology and Solar Energy website. In order to find reliable data, they were compared with other sources of information as for the climate module. In particular, the database elaborated by Mr Robert Van Buskirk, a professor and researcher of the University of Asmara until late ’90, was used for comparisons. Then, to calculate the effective rainfall the *Fixed percentage method* was used (paragraph 3.2.3, “Rain module”). The reason of the choice of this method is that, for rainfall values below the threshold amount of 100 mm/month, like in our case, the rainfall efficiency will be approximately 80%, according with the user’s guide of CROPWAT made by FAO [27].



Station embela **Eff. rain method** Fixed percentage

	Rain	Eff rain
	mm	mm
January	8.4	6.7
February	5.3	4.2
March	15.8	12.6
April	24.3	19.4
May	24.2	19.4
June	26.1	20.9
July	83.1	66.5
August	99.2	79.4
September	35.7	28.6
October	16.1	12.9
November	9.6	7.7
December	7.8	6.2
Total	**355.6**	**284.5**

FIGURE 44 RAIN MODULE

When data are available on the long run, it is possible to produce a reference dry year and a reference wet year, behind the "normal year" obtained by average monthly values. They result from a statistic analysis of rainfall values, calculating for each value of yearly rainfall, the probability that the observed rainfall would be equal to that value. The probability of having a rainfall value greater than a certain threshold (the variable) is imposed at 20% in the case of dry year; it is imposed at 80% in the case of wet year. These reference dry or wet years are used to make estimations in particular condition of extreme drought or unusual rainfalls, and to adjust the calculation of water needs made by the computer program in these exceptional cases.

- ➢ Soil

Soil is a key issue for this particular country, because in the last years it has been involved in a rapid desertification process. Besides this natural phenomenon, many man-inducted activities aggravate the situation, like the expansion of agricultural land, the high dependency on fuel wood as source of household energy and overgrazing.

Initially, a soil map of the entire country was considered, made by a FAO soil researcher ad published as a report [53]:

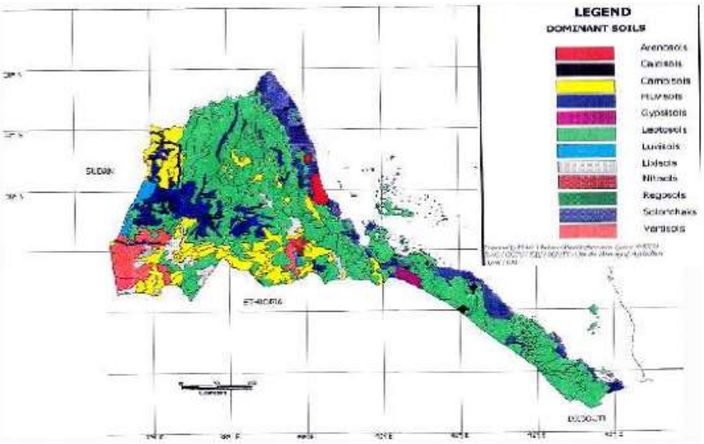


FIGURE 45 THE STATE OF ERITREA: SOIL CLASSIFICATION

The farm under analysis corresponds to a Leptosol type, but this classification is not sufficient to evaluate ground water springs and it is not an unequivocal way to classify a soil. For these reasons, collecting data directly in the field was required.

After a direct investigation in the estate, three main different soils were recognised, mostly because of the presence of the intermittent river Mai Ainis during the year. The river makes loamy the nearest land, at the southern extremity of the farm, mainly because of the flood events; on the contrary, the areas far away from the river are drier and stony like. Another factor is the altitude gradient between the cropped areas that goes from 1677 to 1685m. For this reasons and because no information were available from past investigations, all the three different soils were analysed in order to determine their components. Once known the percentages of sand, silt and clay for the soils, a model was used to calculate the parameters required by the CROWAT Soil Module (see paragraph 3.2.3). The model was suggested by Mr Fekadu Tesfamichael, an Eritrean soil expert. Mr Tesfamichael was introduced to me and the farmers of the Ferrando Ezechiele Agricultural Estate by the minister of Agriculture of the Eritrean government, Mr Arafainet Berke. The Ministry was fully involved during the on field experience and the cooperation with the Minister and his Advisor, Mr Amanuel Negassi Hagos was fundamental to start the collaboration with local professionals.

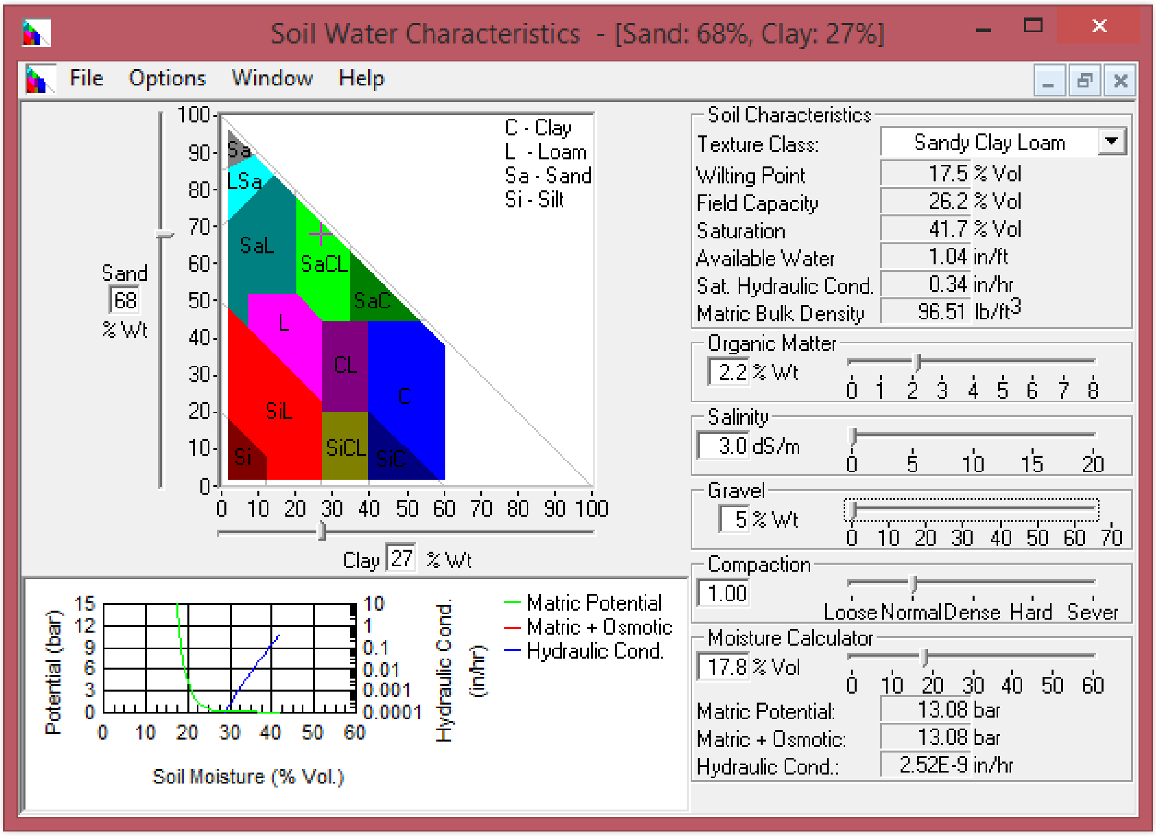
The computer model suggested by Mr Tesfamichael, Soil Water Characteristics (SWC) – Hydraulic Properties Calculator [57], estimates soil water tension, conductivity and water holding capability based on the soil texture, organic matter, gravel content, salinity and compaction. It is developed by USDA Agricultural Research Service in collaboration with Department of Biological Systems Engineering, Washington State University. The input parameters for the SWC are soil texture, salinity and organic matter content. In order to find these values, soil samples had to be collected and analysed by a professional laboratory.

Three different samples of soil, one for each soil type, were collected and they were analysed by the laboratory DIMMS Control. Together with the laboratory experts, the possibility to calculate the parameters required by CROPWAT having no direct measurements upon soil texture was considered. Then, the final decision was to analyse soil content because the parameters are site specific and they affect the most the calculation of water needs.

The information requested to the laboratory were texture of the soil, salinity and compaction. In order to take representative samples of the mixed fraction, the quartering sampling method shall be applied. It involves collecting a certain quantity of soil at 50 cm of depth. Then, the soil has to be divided into four parts of equal dimensions. Two of them are excluded and the remaining soil is subjected to the same procedure. The quartering method is repeated until the sample is heterogeneous and it is preserved in a sealed envelope given by the laboratory. The samples are about 5kg each.

The analyses results of the three soils were used in the Soil Water Characteristics to obtain the parameters required by CROPWAT. The computer program Soil Water Characteristics gives the following results, as reported in Figure 46:

- *Bulk Density*: the total air dry soil mass divided by the total soil volume, (g/cc).
- *Field Capacity* (FC): the water content, (%v), of the soil matrix approximating the water content of a saturated soil that has been allowed to freely drain.
- *Plant Available Water* (PAW): the quantity of water (in/ft; cm/m) that a plant is able to extract from a soil at field capacity, calculated as FC (%v) minus WP (%v) times a depth of soil.
- *Hydraulic Conductivity*: the capability of water to move within the soil matrix driven by matrix and gravitational potentials, (cm/s; mm/hr; in/hr) dependent on soil texture and moisture content.
- *Saturation* (SAT): the saturation moisture content of the soil matrix such that the entire soil porosity is water filled, (% volume), and dependent only on the soil texture and unaffected by salinity or gravel.
- *Tension or Soil Water Potential*: Matrix potential of soil water held within the interstices of soil particles by capillary forces, dependent upon soil texture and moisture content.
- *Wilting Point* (WP): the water content below which plants are generally unable to extract water from the soil.



Soil Water Characteristics - [Sand: 68%, Clay: 27%]

Sand 68 % Wt

Clay 27 % Wt

Soil Characteristics

Texture Class: Sandy Clay Loam

Wilting Point 17.5 % Vol

Field Capacity 26.2 % Vol

Saturation 41.7 % Vol

Available Water 1.04 in/ft

Sat. Hydraulic Cond. 0.34 in/hr

Matric Bulk Density 96.51 lb/ft^3

Organic Matter 2.2 % Wt

Salinity 3.0 dS/m

Gravel 5 % Wt

Compaction 1.00

Moisture Calculator 17.8 % Vol

Matric Potential: 13.08 bar

Matric + Osmotic: 13.08 bar

Hydraulic Cond.: 2.52E-9 in/hr

FIGURE 46 SOIL WATER CHARACTERISTICS-ZONE1

From the parameters seen above, it is possible to calculate the Total Available Water, which depends on the soil texture and its porosity and is defined as $TAW = FC - WP$. For the soils of the farm, the results are shown in Table 16.

The following parameter to determine is the infiltration rate, or the velocity at which water enters into the soil. It is usually measured by the depth in [mm] of the water layer that can enter the soil in one hour. In dry soils, water infiltrates rapidly, but it is not a linear phenomenon. This first behaviour is called initial infiltration rate. As more water replaces the air in the pores, the water from the soil surface infiltrates more slowly and eventually reaches a steady state. This is called the *basic infiltration rate* [58].

In this case, tabulated infiltration rates were researched for similar soils, in terms of texture and hence infiltration, and convert them into the unit required by CROPWAT, i.e. [mm/day]. The tabulated information was available in a FAO document [30], and they are reported in Table 17. The table is the result of a study made by the Natural Resource Management and Environment Department of the Food and Agriculture Organisation. The choice was made using the USDA Soil Triangle (Figure 47), a diagram that allows to identify the soil class of a certain sample. Inserting the three percentages of clay, silt and loam of the soil, a point in the triangle is determined. This is a preliminary test that could be conducted in field, but to have a deeper vision of the soil and crop needs, the investigation about how water infiltrates into the soil should be more accurate. Some field methods to calculate this infiltration rate exist, they use simple measurement instruments like infiltrometers [59].

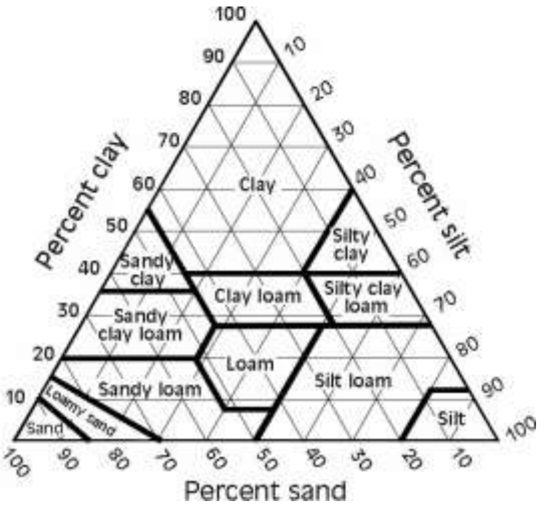


FIGURE 47 USDA SOIL TRIANGLE

SOIL	% CLAY	% SILT	% SAND	SOIL CLASS
Sample 1 (zone 1)	27	6	68	sandy clay loam
Sample 2 (zone 2)	68	7	36	clay
Sample 3 (zone 3)	79	2	19	clay

TABLE 16 SOIL TEXTURE AND CLASSIFICATION

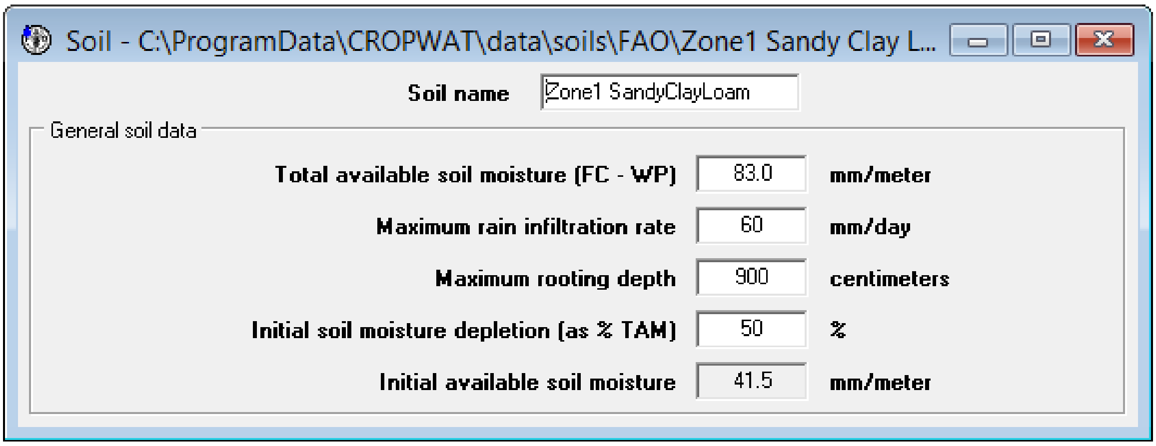
From the table below, the values of basic infiltration rate of similar soils could be obtained, knowing the soil class. Multiplying for the maximum hours of rain in a rainy day (maximum value – 4 hours), it is evaluated the maximum infiltration rate, the parameter used in CROPWAT. The average hours is an information given by farmers' experience, but the value should be monitored because of the remarkable changes in climate worldwide.

Soil type	Basic infiltration rate (mm/hour)
sandy	less than 30
sandy loam	20 - 30
loamy	10 - 20
clay loam	5 - 10
clay	1 - 5

TABLE 17 BASIC INFILTRATION RATES FOR VARIOUS SOIL TYPES

The third parameter to insert in CROPWAT in the soil module is the rooting depth. The rooting depth is 900cm as suggested by the program in absence of data, but the reliability of this value was checked by comparison with standard values for every cultivated crop. The table in [30] reports rooting depth for common crops. This parameter is relevant also in the calculation of the irrigation depth needed by crops, because the capability to attract water depends on how much roots are deep.

Finally, the initial depletion of the soil moisture was chosen. The initial depletion is imposed at 50% of TAW, because the assumption was to start from a semi dry soil to calculate the water requirements. Because there are three different soil types, the farm was divided into three portions and the water requirements were calculated depending on the crops in each area. In the figures below are reported the soil modules inserted in the program.



Soil name: Zone1 SandyClayLoam

Total available soil moisture (FC - WP) 83.0 mm/meter

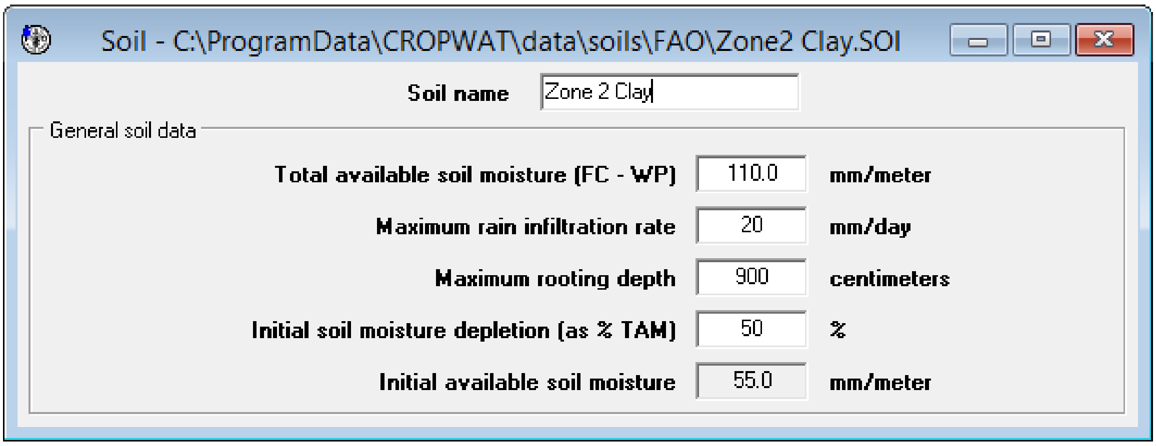
Maximum rain infiltration rate 60 mm/day

Maximum rooting depth 900 centimeters

Initial soil moisture depletion (as % TAM) 50 %

Initial available soil moisture 41.5 mm/meter

FIGURE 48 SOIL MODULE ZONE1



Soil name: Zone 2 Clay

Total available soil moisture (FC - WP) 110.0 mm/meter

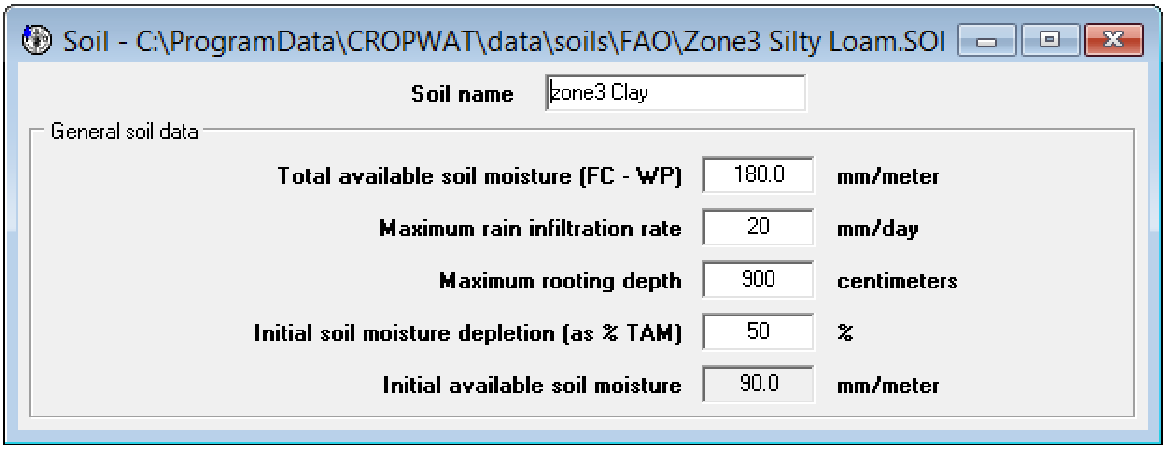
Maximum rain infiltration rate 20 mm/day

Maximum rooting depth 900 centimeters

Initial soil moisture depletion (as % TAM) 50 %

Initial available soil moisture 55.0 mm/meter

FIGURE 49 SOIL MODULE ZONE2



Soil name: zone3 Clay

Total available soil moisture (FC - WP) 180.0 mm/meter

Maximum rain infiltration rate 20 mm/day

Maximum rooting depth 900 centimeters

Initial soil moisture depletion (as % TAM) 50 %

Initial available soil moisture 90.0 mm/meter

FIGURE 50 SOIL MODULE ZONE3

- Crop Patterns

The crop pattern of an agricultural farm is not always the same. It varies every year, depending on the crop rotation, the choices about fertilizers, the yield of the crops linked to a certain soil type. In our case, another unavoidable variable is the availability of water. It depends on yearly precipitations, which are erratic and hardly predictable, and on water management operated by all the farmers along the Mai Ainis river.
To obtain a crop pattern, the assumption was to have all the water needed and to cultivate all the available areas of the farm. Then, considering the effective water content of the wells of the farm, some hypothesis were changed in order to qualitatively consider water shortage, as for the exclusion of the most water intensive crops.
The land has been divided in three parts, because the soil presents differences in texture, hence three CROPWAT sessions were created to evaluate the irrigation schedules and schemes. The three zones are defined as:

- Zone 1: the field supplied by well 1, at the southern extremity of the farm;
- Zone 2: the zone around the central house, served by well 2;
- Zone 3: the last zone delimitated by the paved road and the riverbed, served by well 3.

The red points in Figure 51 represent the wells.

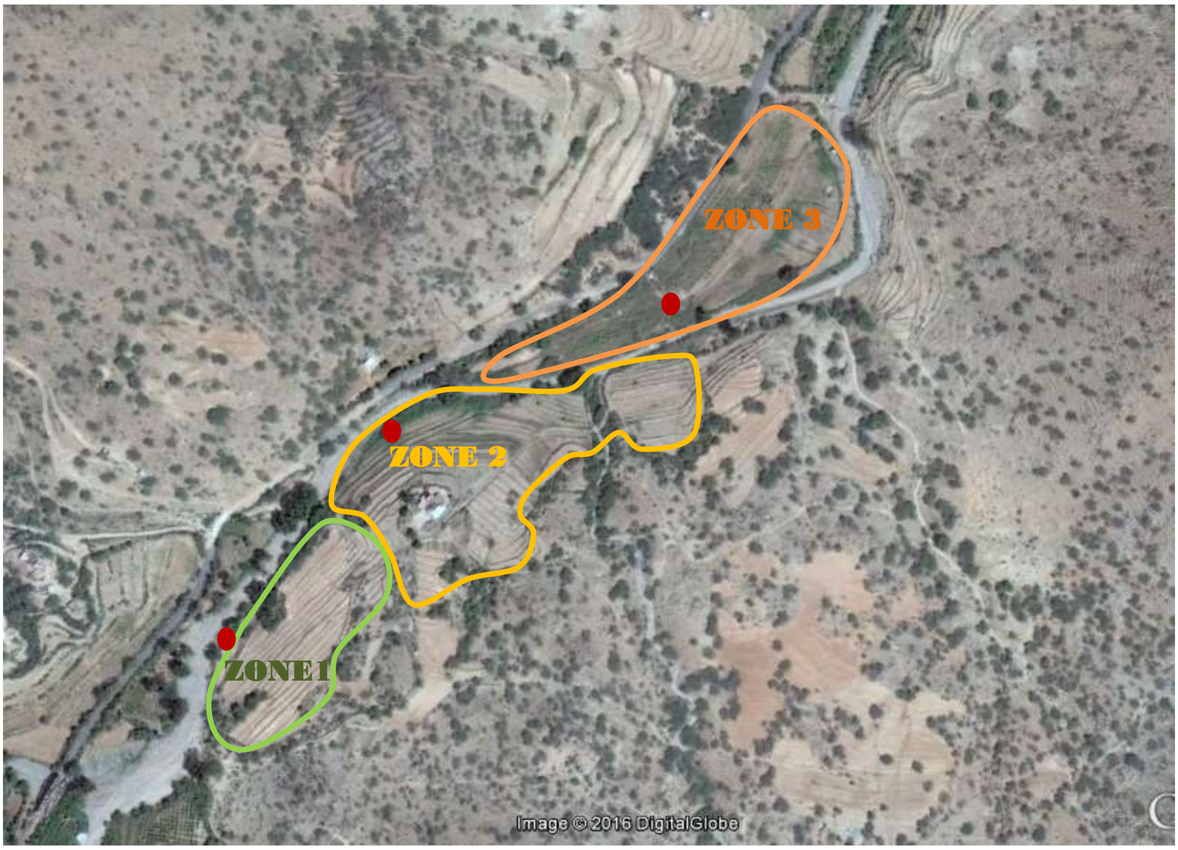


FIGURE 51 GOOGLE EARTH VIEW OF THE FARM AND LAND DIVISION

The division will be used to have three different water distribution networks and to calculate three water and energy demands.
The measure made in the field concerned the value of the cultivable area in [ha], the total area excepting the streets, the house, the canals for irrigation and the areas assigned to the animals. Because there is not a detailed map of the farm, excluded a handmade drawing dated 1956, that does not correspond to the actual land division, all the boarders of the fields were marked and measured. Then, transferring the data collected in a technical drawing program – i.e. ArchiCAD - the surface area was calculated, considering both the existing

cropped zones as much as the non-cultivated ones. The manager of the farm was asked to develop three crop patterns for the three zones the most realistic she could. The results are listed in the tables below.

a) ZONE 1

Total area zone1: 1 ha			
Crop	% Area	Cropped area [m^2]	Planting date
millet	50	5000	April
zucchini	25	2500	July
tomato	25	2500	July

TABLE 18 ZONE 1 CROP PATTERN

b) ZONE 2

Total area zone 2: 2 ha			
Crop	% Area	Cropped area [m^2]	Planting date
Barley	12	2400	June
Apple	1.6	320	Perennial
Peach	2.4	480	Perennial
Maize	41	8200	May/June
Zucchini	4	800	August
Eggplant	6	1200	August
Sweet pepper	5	1000	August
Chicory	3.5	700	March
Basil	3.5	700	March
Spinach	3.5	700	March
Parsley	3.5	700	March
Carrot	3.5	700	March
Salad	3.5	700	March
Chick pea	3.5	700	March
Alp alpha	3.5	700	March

TABLE 19 ZONE 2 CROP PATTERN

c) ZONE 3

Total area zone 3 1.5 ha			
Crop	% Area	Cropped area [m^2]	Planting date
Mango	50	7500	Perennial
Maize	20	3000	June
Napa Cabbage	3	450	September
Green beans	3.86	579	September
Dry beans	3.86	579	September
Cucumber	3.86	579	September
Broccoli	3.86	579	September
Cabbage	3.86	579	September
Cauliflower	3.86	579	October
Chilli peppers	3.86	579	May

TABLE 20 ZONE 3 CROP PATTERN

Through data about crop patterns, the water needs of the crop patterns was finally calculated, for each month of the year. CROPWAT calculates the water requirement and the net irrigation requirement, which is CWR minus the natural contributions, it is called "precipitation deficit". The values are summarized in the tables below, in evidence the month with the higher water request. This specific value is used to design the conveyance system and the nominal power of the pumping system.
Then, considering the irrigation technique applied through efficiencies, gross irrigation requirement is obtained in the following section.

ZONE 1	Precipitation deficit [mm]		
month	Small Vegetables Zucchini	Tomato	Millet
Jan	0	0	0
Feb	0	0	0
Mar	0	0	0
Apr	0	0	36.5
May	0	0	234.1

Jun	0	0	332.8
Jul	167.4	68.2	146.6
Aug	239.2	130.7	0
Sep	291.8	291.6	0
Oct	24.1	305.6	0
Nov	0	235	0
Dec	0	35.7	0

TABLE 21 ZONE 1 NET SCHEME IRRIGATION REQUIREMENT

ZONE 2	Precipitation deficit [mm]						
	Small veg Hatchery	Maize	Fruit tree	Barley	Sweet Peppers	Small veg Zucchini	Small veg Eggplant
Jan	0	0	211.5	0	0	0	0
Feb	0	0	217.3	0	0	0	0
Mar	192.7	0	292.1	0	0	0	0
Apr	276.2	0	339	0	0	0	0
May	316	0	389.7	0	0	0	0
Jun	29	91.7	403.6	122.8	0	0	0
Jul	0	259.3	356.5	310.9	0	0	0
Aug	0	317.5	274.5	297.7	105	144.3	79.6
Sep	0	235.2	0	161.9	217	272	225.4
Oct	0	7.3	0	0	278.2	272.6	276.7
Nov	0	0	0	0	229.9	21.7	129.7
Dec	0	0	0	0	19	0	0

TABLE 22 ZONE 2 NET SCHEME IRRIGATION REQUIREMENT

ZONE 3	Precipitation deficit [mm]								
	Maize	Mango	Dry bean	Cabbage	Gr bean	Veg Cauliflow.	Veg Chili	Veg Napa Cabbage	Veg Broccoli
Jan	0	189.7	0	238.1	0	0	20	121	0
Feb	0	195.2	0	95.2	0	0	0	0	0
Mar	0	240.6	0	0	0	0	0	0	0
Apr	0	257.4	0	0	0	0	0	0	0
May	0	316.7	0	0	0	0	0	0	205.7
Jun	92.1	368	0	0	0	0	0	0	311
Jul	265.5	341.1	0	0	0	0	0	0	286.3
Aug	325.6	310.8	0	0	0	0	0	0	17.3
Sep	239.7	343.1	102.6	176.2	66.3	97.1	0	0	0
Oct	7.3	308.1	261.7	183.9	182.6	213.7	177.9	92.2	0
Nov	0	245.9	261.9	203.3	239.5	238.4	220.7	184.6	0
Dec	0	219.7	92.3	228.8	91.3	127.5	225.6	228.7	0

TABLE 23 ZONE 3 NET SCHEME IRRIGATION REQUIREMENT

Irrigation techniques applied

The net water request is augmented in order to take into consideration the efficiency of the irrigation method used. water losses are due to conveyance losses and field losses, as explained in paragraph 2.3.2.
Considering the amount of water to be extracted, the energy required and the availability of energy sources, each well type could be coupled with a pumping system and a conveyance system, behind the choice about the irrigation method. There are several inputs and parameters that affect the decision making process, but not all variables are equally weighted. The fundamental aspects of interest are climate and rainfall during the year, the availability of surface and groundwater resources, the distance between water and fields and the reliability of the water resource.
The suitability of the various irrigation methods, which can be rearranged in three main techniques, i.e. surface, sprinkler or drip irrigation [43], depends mainly on the following factors:

- natural conditions
- type of crop
- type of technology
- previous experience with irrigation
- required labour inputs
- costs and benefits.

The *natural conditions* such as soil type, slope, climate, water quality and availability, could have different impacts on the choice of an irrigation method. As an example, sandy soils have a low water storage capacity and a high infiltration rate. They therefore need frequent but small irrigation applications, in particular when the sandy soil is also shallow. Under these circumstances, sprinkler or drip irrigation are more suitable than surface irrigation. On loamy or clay soils, all three irrigation methods can be used, but surface irrigation is more commonly found, probably because of its simplicity. Clay soils with low infiltration rates are ideally suited to surface irrigation, because it eases water standing and this is favourable since poor water infiltration rate. When a variety of different soil types is found within one irrigation scheme, sprinkler or drip irrigation are recommended as they will ensure a more even water distribution. Sprinkler or drip irrigation are preferred above surface irrigation on steeper or unevenly sloping lands as they require little or no land levelling. For what concerns other climatic parameters, strong wind can disturb the spraying of water from sprinklers. Under very windy conditions, drip or surface irrigation methods are preferred, but wind could lead to higher evaporation rates in surface irrigation. In areas of supplementary irrigation, sprinkler or drip irrigation may be more suitable than surface irrigation because of their flexibility and adaptability to varying irrigation demands on the farm. Water application efficiency is generally higher with sprinkler and drip irrigation than surface irrigation and so these methods are preferred when water is in short supply.

Surface irrigation can be used for all *types of crops*. Sprinkler and drip irrigation, because of their high capital investment per hectare, are mostly used for high value cash crops, such as vegetables and fruit trees. They are seldom used for the lower value staple crops. Drip irrigation is suited to irrigate individual plants or trees or row crops such as vegetables and sugarcane. The main disadvantage of the drip system is that it is usually permanent. Water is applied frequently, every 2 or 3 days, and on clay soils, water should be distributed slowly to avoid water ponding and runoff. Drip irrigation usually use PVC pipes to supply water, through mainlines, sublines and laterals which could be very little in diameter (13-20 mm according to [43]). Every emitter is dedicated to one single plant, or the configuration could provide more than one emitter to one single plant, as it happens for trees.

The *type of technology* affects the choice of irrigation method. In general, drip and sprinkler irrigation are technically more complex methods. The purchase of equipment requires high capital investment per hectare. To maintain the equipment a high level of 'know-how' has to be available. In addition, a regular supply of fuel if required for pumping must be maintained and spare parts should be accessible.
Surface irrigation systems - in particular small-scale schemes - usually require less sophisticated equipment for both construction and maintenance (unless pumps are used). The required equipment is often easier to maintain and less dependent on the availability of foreign currency for spare parts substitution.

The choice of an irrigation method also depends on the *irrigation tradition* within the region or country. Introducing a previously unknown method may lead to unexpected complications. It is not certain that the farmers will accept the new method. The servicing of the equipment may be problematic and the costs may be higher compared to the benefits. Often improving the traditional irrigation method could be easier than introducing a totally new method.

Surface irrigation often requires a much higher *labour input* for construction, operation and maintenance than sprinkler or drip irrigation. Surface irrigation requires accurate land levelling, regular maintenance and a high level of farmers' organisation to operate the system. Sprinkler and drip irrigation require little land levelling; system operation and maintenance are less labour-intensive.
Before choosing an irrigation method, the costs and benefits of the available options should be evaluated. On the cost side not only the construction and installation, but also the operation and maintenance should be taken into account. These costs should then be compared with the expected benefits, such as the increased field yields of agricultural products. It is obvious that farmers will only be interested in implementing a certain method if they consider it economically attractive.

In conclusion, surface irrigation is by far the most widespread irrigation method. It is normally used when conditions are favourable: mild and regular slopes, soil type with medium to low infiltration rate, and a sufficient supply of surface or groundwater. In the case of steep or irregular slopes, soils with a very high infiltration rate or scarcity of water, sprinkler and drip irrigation may be more appropriate. When introducing sprinkler and drip irrigation it must be ensured that the equipment can be maintained on the long run.

To choose the irrigation methods to simulate in the case study, all the advantages and disadvantages of the various techniques are evaluated together with the farmers. The final choice is the one that suits the best local conditions and, when possible, it is suggested a testing phase for every method in order to choose the one that gives best results. Water availability is the main constraint of the decision making process, but also its quality affects the choice: sprinkler and drip irrigation may require high maintenance if there are much sediments in water. Furthermore, economic considerations tend to push for an expensive solution as drip or sprinkler irrigation, but only if addressed to high value cash crops, such as vegetables and fruit trees. Because trees are perennial crops, developing a drip scheme, which is permanent, could be advantageous. In case of rotating crops, it could represent a limit. Nevertheless, in the farm only few perennial fruit trees are cultivated, mango, apple and peach trees. The mango trees are not perennial in the real sense, but they last for around 6 years and considering that they are the most water intensive crop of all the farm, they were excluded in the second cycle of analysis, when there were made considerations to deal water scarcity. For apple and peach trees, they were also excluded by further analyses because of their low number (only 100 trees in total) and because in three years of cultivation, they have not given any harvest, probably because of water scarcity. For a future enlargement of this project, drip irrigation can surely enter into the new irrigation options if the cultivation turns into perennial crops. During the visit to the Ferrando Ezechiele farm, another problem arose, the problem of the hyenas. During drought periods, while the Mai Ainis River is dry, hyenas look for water inside the farms along the river and when they feel there is water inside pipes, they try to reach it. During the round trip, a total of 16m in length of PVC pipes were irretrievably damaged by hyenas. The problem is frequent and because the farm is not fenced and not even supervised during the night, the only solution adopted is to avoid PVC pipes as much as possible. Considering all these factors, drip irrigation was excluded by the analyses.

Water quality affects the choice of the irrigation system, the type of nozzle and the treatments the water should undergo. During the designing process, in order to evaluate the kind of water, four parameters are considered:

- Salinity, for the osmotic consequence upon the plant;
- Alkalinity, for sodium results on soil hydrologic characteristics decay;
- Toxicity, for plants damage and nutrient disequilibrium;
- Total solids, for risk of nozzle occlusion

During the visit to the Ferrando Ezechiele Agricultural Estate, the Ministry of Land, Water and Environment was involved, thanks to the collaboration with the minister of Agriculture, Mr Arefaine Berhe. Mr Tesfamichael Keleta, hydrogeologist and director of the Water Resource Assessment and Information, and Semere Berhe, hydrogeologist and Unit head of the Water Resource Department, came to the farm to do measurements about the three existing wells. They also took a water sample to analyse it in their laboratory in the capital Asmara. Their help and their knowledge were extremely precious to understand the importance of water quality in the decision making process about the irrigation system.
The results obtained refer to well number 2 and they are resumed in the tables below:

	El. Conductivity	pH	TDS	Temper	T. Hardness	T. Alkalinity	Turbidity	Cl2
MPL	2000 µS/cm	6.5-9.2	1500 mg/l		500mg/l		<5NTU	2.0 mg/l
Results	1247	6.95	835	21	550	400	1.3	0

TABLE 24 GENERAL DESCRIPTION OF THE WATER

Cations	Ca	Mg	Na	K	Fe	Mn	NH3
MPL in WHO standards	200mg/l	150mg/l	200mg/l	12mg/l	0.3mg/l	0.5mg/l	1.5mg/l
Results in PPM (mg/l)	136	49.1	34	5	0.01	0.01	0.63
Anions	HCO3	CO3	SO4	Cl	NO3	F	NO2
MPL in WHO standards			400mg/l	600mg/l	50mg/l	2.0mg/l	3.0mg/l
Results in PPM (mg/l)	488	0	160	32	13.29	0.1	0

TABLE 25 HYDRO CHEMICAL DATA

SAR	Sum of Cations	Sum of Anions	electro neutrality	Water Type
	In meq/l	In meq/l	%	
	12.45	12.49	3.2	Ca-Mg-HCO3-SO4

TABLE 26 CALCULATED DATA

Incubation time	Incubation temperature	Method	Results
18-24 hrs	37	Membrane-Filtration	Total-Coliforms/100ml
	44.5		Faecal-Coliforms/100ml

TABLE 27 BACTERIOLOGICAL DATA

The suitability of one method compared to others, depends on its capacity to minimize the following risks: for salty water, infiltration problems and reduction in production; for wastewater, toxicity risk for plants, risk of microbiological damages for products. In general, using water with high toxic and microbiological risk is not suggested to turn to sprinkling methods, while drip irrigation seems more suitable. In case of high values of total solid, the occlusion risk should be carefully evaluated. Micro-irrigation is particularly appropriate with high salinity water, because it allows maintaining the soil humidity at high values, avoiding salt concentration in flowing water. It is possible even through sprinkler irrigation, but frequent applications could originate toxicity damages to leaves [60].

As shown from the results of the water analysis, the springs from which water is extracted are good in terms of salinity, total solids and bacterial ranges. However, it would be useful to constantly supervise the distribution system and the delivery points. Changes in chemical contents and in water salinity could lead to significant yield reduction.

Thanks to the information collected by the collaborators of the Ministry of Land, Water and Environment about water quality and considering the operation and maintenance requisites, the choice about the irrigation methods to consider was made. Hence, three cases are considered:

- Traditional method or furrow irrigation (earthen canals) *CASE1*
- Low pressure pipe irrigation *CASE2*
- Sprinkler irrigation *CASE3*

Considering the net water requirement for each crop calculated thanks to CROPWAT available into decade or into monthly value, the *gross* irrigation requirements is obtained passing through efficiencies of each irrigation technique.

Method	ea	ec	Total Efficiency
Traditional	60%	70%	42%
Pipe system	60%	95%	57%
Sprinklers	75%	95%	71%

TABLE 28 EFFICIENCIES OF SELECTED IRRIGATION TECHNIQUES

After passing into daily values dividing for the number of days in a month, the crop water need F is determined, in $\left[\frac{mm}{day}\right]$ for every crop. It should be reminded that this value represents the quantity of water that must be supplied through irrigation. It is the difference between ET_C and natural contributions as rainfall or "precipitation deficit", as called in paragraph 3.2.

In order to find the flowrate during the *worst* month in terms of water demand, given the irrigation techniques, a procedure found into a technical handbook [44] was used. Determining the water volume to distribute depends only on two factors: the soil type or its capacity to contain water, in other words its porosity, and the ability of the particular crop to attract water through its roots. The porosity is translated in the total available water (TAW), the difference between Field Capacity (FC) and the wilting point (WP). Not all the TAW could be used by a plant, only the quantity that roots are able to attract. This value depends on the depth reached by roots inside the soil. To count for this restriction, TAW is decremented by the fraction the plant is not able to reach, through a multiplier (z_i, expressed in centimetres). Moreover, before the water content in a soil reaches the WP, the plants can be stressed by the decreasing water availability. This is the reason why a coefficient should be introduced and multiplied by TAW, giving the value of critic water disposal p_i. The p_i varies with crop type, z_i, ET_i and soil type. The formulas used are the same in paragraph 3.2. Under the critic value p_i, the plant suffers water scarcity. It is the readily available water, RAW. Then, water is still available, but the plants make a greater effort to extract it. Each crop has a specific coefficient of stress p_i as it happens for the rooting depth coefficient z_i.

After calculating RAW_i or net water volume, that represent the volume of water every crop should receive not to be stressed, the minimum period between two irrigation actions (T_i, in days) could be evaluated and it is valid for both net and gross values:

$$T_i = \frac{RAW_i}{F_i} = \frac{RAW_{i,gross}}{F_{i,gross}} \; [days]$$

$$RAW_{i,gross} = \frac{RAW_i}{\eta}$$

$$F_{i,gross} = \frac{F_i}{\eta}$$

η is the irrigation efficiency;

F_i is daily water need, determined through CROPWAT.

At this point, the volume of water to distribute for each crop and the intervals between two following actions could be calculated. Moreover, the total number of actions for a crop is obtained through the growing season N (expressed in days) and the other variables of interest are found thanks to the equations explained in section 3.2. In the tables below, main results are listed and it should be noted that the parameter p is changed in p^* because of the soil in which the plant grows. For sandy soil it is increased, on the contrary for clay soils it is decreased.

ZONE 1	TAW [mm/m] 83		
	Small Vegetables	Tomato	Millet
$F_i\ \left[\frac{mm}{day}\right]$	0.00	0.00	11
$z_i\ [m]$	0.8	0.7	0.60
p	0.5	0.5	0.45
p^*	0.55	0.55	0.50
$RAW\ [mm]$	36.52	31.96	24.65
$T_i\ [days]$	-	-	3
n	-	-	108
$N\ [days]$	95	145	240
$RAW_{gross42\%}\ [mm]$	86.95	76.08	58.69
$i_{42\%}\ \left[\frac{l}{s \cdot ha}\right]$	-	-	3.05
$Q_{42\%}\ \left[\frac{l}{s}\right]$	-	-	8.1
$RAW_{gross57\%}\ [mm]$	64.07	56.06	43.25
$i_{57\%}\ \left[\frac{l}{s \cdot ha}\right]$	-	-	2.25
$Q_{57\%}\ \left[\frac{l}{s}\right]$	-	-	6
$RAW_{gross71\%}\ [mm]$	51.44	45.01	34.72
$i_{71\%}\ \left[\frac{l}{s \cdot ha}\right]$	-	-	1.81
$Q_{71\%}\ \left[\frac{l}{s}\right]$	-	-	4.8

TABLE 29 RESUME OF MAIN PARAMETERS OF ZONE 1

In zone 2, apple and peach trees were excluded from calculation after a first step of analysis, due to their high water needs not compensated by a remarkable yield. The trees were planted three years ago, after a governmental project, which included the distribution of fruit trees to farmers and a couple of cattle to pastors. In the Ferrando Ezechiele farm, 100 trees were planted, but not even one of them have ever given a fruit, probably because of climate and water scarcity.

ZONE 2	TAW [mm/m] 110				
	Small Veg Hatchery	Maize	Barley	Small Veg Zucchini	Small Veg Eggplant
$F_i\ \left[\frac{mm}{day}\right]$	0.00	10.58	7.92	4.81	2.65
$z_i\ [m]$	0.8	0.7	0.5	0.6	0.4
p	0.5	0.5	0.45	0.35	0.45
p^*	0.45	0.45	0.41	0.32	0.41
$RAW\ [mm]$	39.60	34.65	22.28	20.79	17.82
$T_i\ [days]$	-	4	3	5	7
n	-	24	80	19	14
$N\ [days]$	125	95	240	95	95
$RAW_{gross42\%}$	94.29	82.50	53.04	49.50	42.43
$i_{42\%}\ \left[\frac{l}{s \cdot ha}\right]$	-	2.41	2.05	1.15	0.72
$Q_{42\%}\ \left[\frac{l}{s}\right]$	-	18.9	4.7	1.3	1.4
$RAW_{gross57\%}$	69.47	60.79	39.08	36.47	31.26
$i_{57\%}\ \left[\frac{l}{s \cdot ha}\right]$	-	1.77	1.51	0.84	0.53
$Q_{57\%}\ \left[\frac{l}{s}\right]$	-	13.9	3.4	1	1.1
$RAW_{gross71\%}$	55.77	48.80	31.37	29.28	25.10
$i_{71\%}\ \left[\frac{l}{s \cdot ha}\right]$	-	1.43	1.21	0.68	0.43
$Q_{71\%}\ \left[\frac{l}{s}\right]$	-	11.2	2.7	0.8	0.8

TABLE 30 RESUME OF MAIN PARAMETERS OF ZONE 2

In zone 3, all the crops in land were firstly considered, including the more water intensive. Then, to take into consideration that the area is periodically subjected to drought events, two of them were excluded: mango and crucifers. Moreover, the type of mango cultivated in the farm last only few years and harvest in 2015 was the last one. It was a kind of experiment to cultivate this crop and this is why, the next analyses did not continue to consider it.

ZONE 3	TAW [mm/m] 180						
	Maize	Dry beans	Green beans	Small Veg Cauliflow.	Small Veg Chili peppers	Small Veg Napa cabbage	Small Veg Broccoli
$F_i \left[\frac{mm}{day}\right]$	7.99	3.42	2.21	3.24	0.00	0.00	0.00
$z_i\ [m]$	0.8	0.6	0.5	0.6	0.4	0.3	0.4
p	0.5	0.45	0.45	0.35	0.45	0.3	0.45
p^*	0.45	0.405	0.405	0.315	0.405	0.27	0.405
$RAW\ [mm]$	64.80	43.74	36.45	34.02	29.16	14.58	29.16
$T_i\ [days]$	9	13	17	11	-	-	-
n	14	9	6	9	-	-	-
$N\ [days]$	125	110	90	95	95	95	95
$RAW_{gross42\%}$	154.29	104.14	86.79	81.00	69.43	34.71	69.43
$i_{42\%} \left[\frac{l}{s \cdot ha}\right]$	2	0.98	0.67	0.88	-	-	-
$Q_{42\%} \left[\frac{l}{s}\right]$	12.9	1.8	22.1	1	-	-	-
$RAW_{gross57\%}$	113.68	76.74	63.95	59.68	51.16	25.58	51.16
$i_{57\%} \left[\frac{l}{s \cdot ha}\right]$	1.62	0.72	0.49	0.65	-	-	-
$Q_{57\%} \left[\frac{l}{s}\right]$	10.5	1.3	16.3	0.7	-	-	-
$RAW_{gross71\%}$	91.27	61.61	51.34	47.92	41.07	20.54	41.07
$i_{71\%} \left[\frac{l}{s \cdot ha}\right]$	1.18	0.58	0.4	0.52	-	-	-
$Q_{71\%} \left[\frac{l}{s}\right]$	7.6	1.1	13	0.6	-	-	-

Table 31 Resume of main parameters of zone 3

The total flowrate used to design the distribution network is the sum of all the flowrates calculated for each crop inside the three areas.

Design of the water distribution network

1) Traditional irrigation and low-pressure pipe irrigation

The distribution network was designed ex novo for every zone and every type of irrigation method chosen with the aim to reduce as much as possible energy losses. At last, there were nine cases to design. The procedure followed has different steps and it begun during the visit to the farm. The map elaborated through ArchiCAD allows to find the spatial coordinates of the areas of the estate. Thanks to the software, the coordinates were fixed and they were used to design the conveyance system.

The network, including the tanks, the pipes or canals, the nodes (that represent the outlet points), the pump stations, was designed through another software, EPANET 2.0 [61]. It allows the user to realise the network and to simulate the water flow. The simulations were used to modify the initial values of the variables in order to minimise the investment cost on one hand, and to reduce the unit head loss of the pipes on the other. The variable parameter was pipe diameter, on which depends flow velocity. Increasing the diameters of the pipes would cause lower distributed energy losses, but greater investment costs and vice versa, smaller diameters would increase energy losses but decrease investment cost. At the beginning, only the water demand for each node of the network and the dimension of the tank that supplied the water were imposed, beside the x-y-z coordinates. After the first simulation, results were exported in excel format to adjust diameters so that water velocity was not above 0.8m/s [60]. Then, the new values were reported in the EPANET scheme to simulate the real flows and velocities.

The area of each zone was divided in pieces due to geographical and spatial considerations, both for traditional irrigation and low-pressure pipe irrigation. Each node corresponds to an outlet flow rate that is obtained considering the same approach used to calculate total water needs, scaled to the effective dimension of each piece of land. Considering all the outlet points of the networks, the total flowrates moved by pumps or that exit from tanks, correspond to the value of Table 29, Table 30, Table 31. For the second case (low-pressure pipe irrigation), canals are replaced by low pressure pipes, in open configuration. In this case, the total area is divided in sectors, each one fed by a valve in secondary pipes. The sector surface is designed in order to limit the number of feeding points but at the same time to guarantee a good distribution of water. For the sake of simplicity, the network does not contain the exact number of outlet points, but every secondary pipe has two nodes placed at its extremities. They represent half the outlet points placed along the pipe, so that simulations could calculate energy losses through a function that counts for concentrated losses, but the scheme is simple to modify. The results were verified through some manual calculations. EPANET could simulate the head loss inside the pipes in three ways: Hazen-Williams formula, Darcy-Weisbach formula, Chezy-Manning formula. The general equation is:

$$h_L = Aq^B$$

Where h_L is the headloss per unit meter, q is the flowrate, A is the resistance coefficient and B is the flow exponent. For the resistance coefficients, a list of general ranges was used and age factor was considered during the analyses. In this thesis the Hazen-William formula was used, because of its simplicity. The complete equation is:

$$h_L = (4.727 \cdot C^{-1.852} \cdot d^{-4.871}) \cdot q^{1.852}$$

Where C is the Hazen-Williams roughness coefficient and it depends on pipe material and age, d is the pipe diameter. The values used derives from [61].

Minor head losses (also called local losses) are caused by the added turbulence that occurs at bends and fittings. The importance of including such losses depends on the layout of the network and the degree of accuracy required. They can be accounted for by assigning a minor loss coefficient to the pipe. The minor head loss becomes the product of this coefficient and the velocity head of the pipe, through the equation:

$$h_L = K \cdot \left(\frac{v^2}{2g}\right)$$

where K is the minor loss coefficient, v is flow velocity and g is acceleration of gravity. For every pipe the loss coefficient could be inserted, counting for all the outlet points, the curves, tees, elbows and pipe shrinkages.

Same considerations are made for the three zones, with the only exception for zone 3 case 2, where the network scheme is closed. The reason is that the area is bigger and for simulation purposes, energy losses are better described by a closed scheme. Zone 2 and 3 could seem similar in terms of dimensions, but zone 2 is more fragmented than zone 3 and so it is the network. That causes the presence of many different sub-areas (four) with lower water request in zone 2.

Examples of the schemes are reported in the figures below.

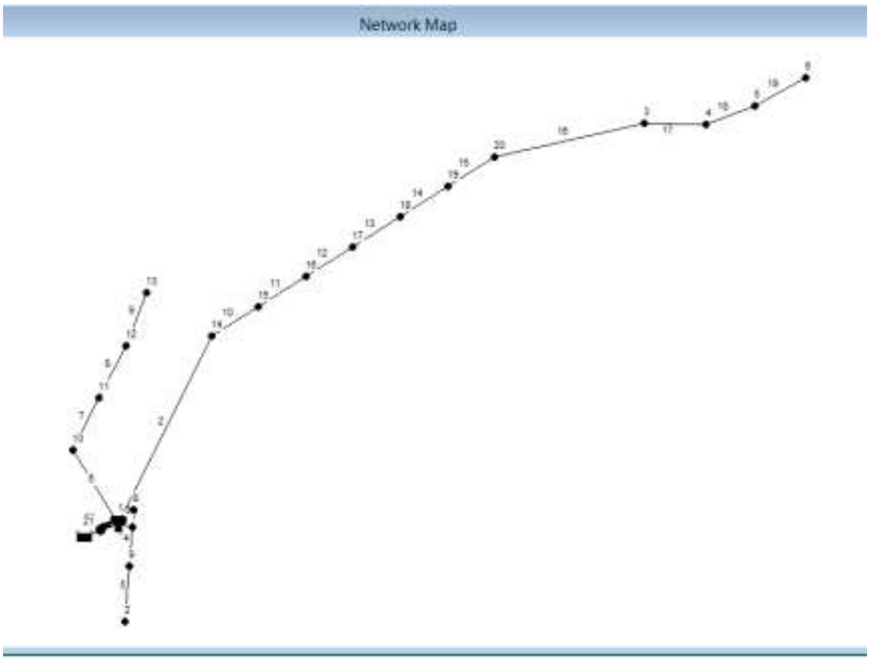


FIGURE 52 ZONE 2 TRADITIONAL IRRIGATION NETWORK

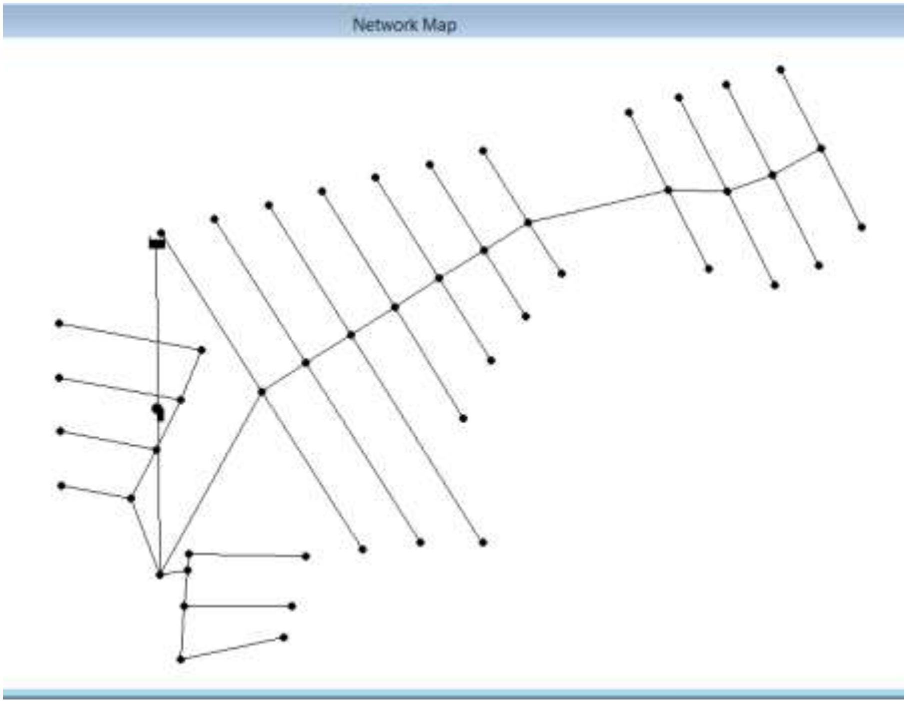


FIGURE 53 ZONE 2 LOW-PRESSURE PIPE IRRIGATION NETWORK

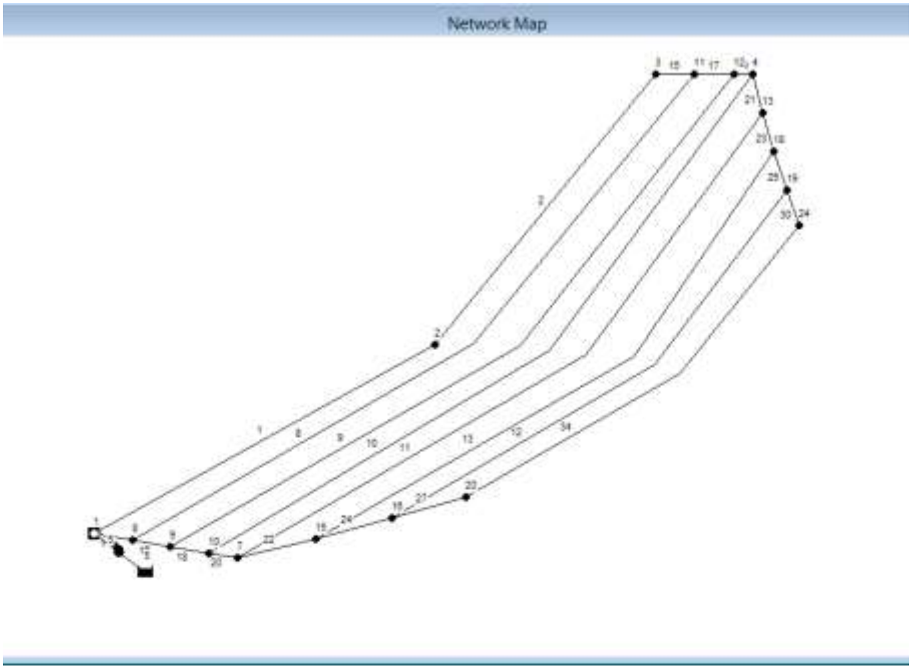


FIGURE 54 ZONE 3 LOW-PRESSURE PIPE IRRIGATION NETWORK

2) Sprinkler irrigation

Designing a sprinkler system requires a more detailed description because the technology is completely different from surface irrigation. It reproduces natural raining conditions, it avoids soil levelling, it saves water and it is independent from loam quantity in the soil, which, on the contrary, is a constraint for the other cases. On the other side, it is more expensive in terms of initial investment, it requires higher pressure level and in windy conditions, it wastes water by evaporation at higher rate [60].

The purpose of the designing step for a sprinkler irrigation system is to choose the devise that fits the best the demand side at the minimum cost. The aim is to find the solution that requires a number of sprinklers as little as possible.

Initially, the average wind speed of the location of interest was considered to obtain a decreased value of range for sprinklers. If compared to nominal range, indeed, sprinklers real range could be lower because technical resources refers to ideal testing conditions. They may be adversely affected by wind and other factors. With a new value of range, a sprinkler was chosen using as decisive parameters the range and the flow rate. It is important to underline that the choice should be suitable for all the three zones, to avoid having different sprinklers, which means maintenance differences and different operation condition. Considering the context, the farmers' acceptance of the technology is crucial to maintain it working for the entire lifetime. This is why a solution with only one type of sprinkler is largely more accessible. For terraced areas, like the ones in the farm of interest, the pipes should follow the terraces to distribute water as uniformly as possible. To avoid inefficiencies, pipes could go along the slope of the land, fed from the top of the slope, obtaining in this way an energy saving. The only foresight is to dispose pressure regulators every time head gradient overcomes by 20% the average value. The pressure analyses along the pipes show that only in zone 2 pressure regulators are necessary. Water is pumped with adequate pressure for the highest delivery point, hence the pressure minimum level is guaranteed everywhere. If pressure in the lower areas is too high, pressure regulators are disposed. After these considerations, the land was divided in sectors to decrease the flowrate in the pipes while designing the network. It is suggested that sectors surface is constant to simplify the network design, but it could vary depending on many factors:

- Geomorphological characteristics of the plot;
- Presence of natural obstacles or infrastructures;
- Cropping techniques;
- Existing primary pipes.

Decisions about number, dimensions and form of the sectors influences the economy and the good functioning of the irrigation system. Optimization process is not carried out analytically for the complexity of calculations, it is delegated to the designer's experience. About dimensions, sectors should be as similar as possible to each other to use all the water distributed in an effective way. The form depends on the plot of the land but the most preferable is the rectangular one. At this point, filling the sectors with sprinklers considering its range gives the number of devices, considering a triangular filling method or a square one (Figure 55).

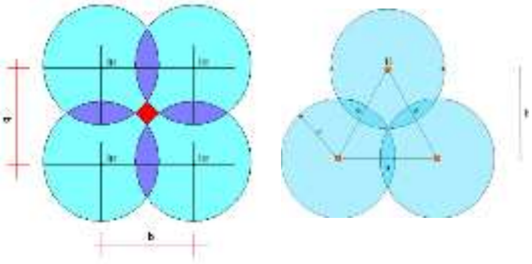


FIGURE 55 SQUARE AND TRIANGULAR FILLING METHOD

To distribute water in each sector, one central pipe from which the secondary pipe with the sprinklers starts could be sufficient; in other cases, it might be necessary to divide the flowrate in more than one feeding pipe and to dispose for every one of them secondary pipes with sprinklers. The secondary pipes may be on both side of the main pipes or only on one side, in first case they are smaller and cheaper but the design is more accurate. Depending on the slope of the land, it is possible to choose a lateral feeding or a central feeding, looking for the less expensive combination of diameters and length.

The calculation and the iteration process starts with the wind check considering for each zone the case with higher water request. For values higher than 5km/h the range decrease by 10% and by additional 2.5% every 1.6km/h [60].

	Zone 1	Zone 2	Zone 3
Wind speed [km/h]	14	16	12
Range decrease	22.5%	25%	20%

TABLE 32 WIND EFFECT ON SPRINKLERS RANGE

Even if the reduction is considerable, the sprinkler system remains a good and valuable option because of the easy realisation, especially considering that the alternative drip irrigation requires a careful analysis of rotating crops and a more accurate irrigation schedule.
Specific literature gives the maximum sprinkler rain intensity in relation to soil texture, as follows:

Texture	Slope , %			
	0-5	5-8	8-12	12-16
Sandy soil, 1.8m depth	50	38	25	13
Sandy soil upon compact layer	38	25	19	10
Medium-textured sandy soil, 1.8m depth	25	20	15	10
Medium-textured sandy soil upon compact layer	19	13	10	8
Medium-textured loamy soil, 1.8m depth	13	10	8	5
Medium-textured loamy soil upon compact layer	8	6	4	2.5
Loamy soil	4	2.5	2	1.5

TABLE 33 MAXIMUM INFILTRATION RATE – MM/H

Results for the three zone are shown below, considering a disposal of the sprinklers in triangular way and the height of the sprinklers' nozzle found in literature [60]:

	Zone 1	Zone 2	Zone 3
Slope	3.5 %	4.3 %	3 %
Maximum infiltration [mm/h]	50	13	13
Maximum flow rate [l/s]	9.64	2.51	2.51
Sprinkler height [m]	0.9	0.3	0.3

TABLE 34 MAXIMUM INFILTRATION RATE

The sprinkler chosen, after some attempts, is the Senninger series 40, reporting the technical resources in Appendix B. Using ArchiCAD, the network was elaborated and the position of each sprinkler was refined in order to distribute water uniformly. Then, the water distribution network is designed through EPANET as in previous cases. In the following figures, areas 1 Figure 56 and 3 Figure 57 are displayed to show the overlapping surfaces fed by the sprinklers. The filling method is the triangular one and this arrangement makes the water supply more effective. The horizontal and vertical distance between two sprinklers is given by the formulas reported in [60]:

$$d_{horizontal} = 85\% \cdot 2r$$
$$d_{vertical} = 75\% \cdot 2r$$

r is the throw or the range of the sprinkler.

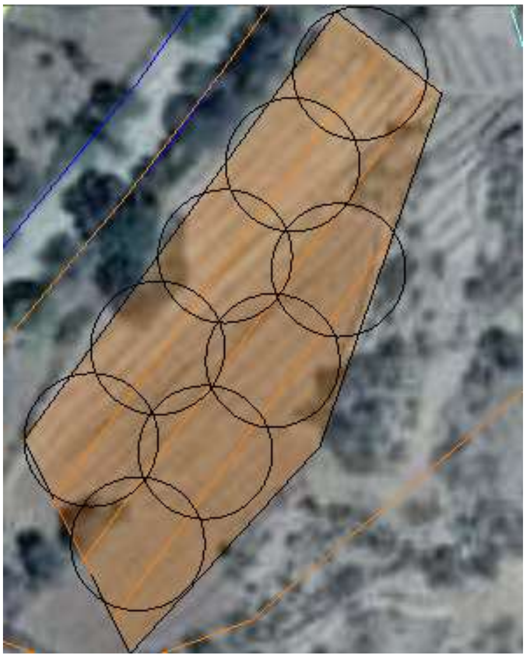


FIGURE 56 ZONE 1 SPRINKLER SYSTEM

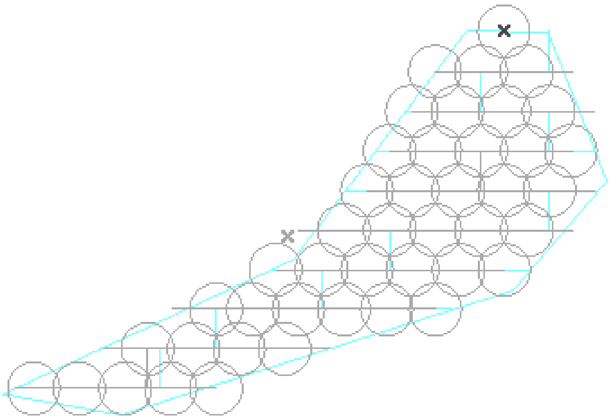


FIGURE 57 ZONE 3 SPRINKLER SYSTEM

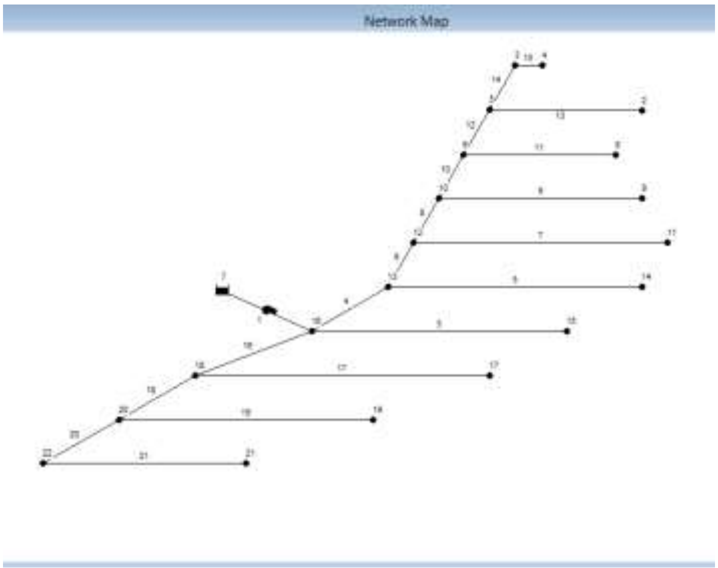
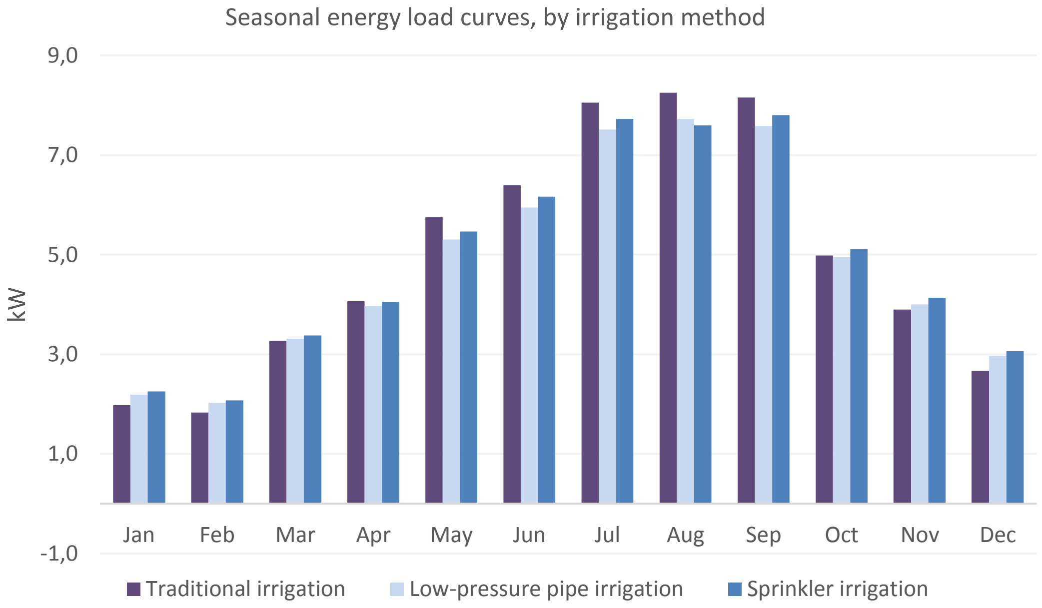


FIGURE 58 ZONE3 SPRINKLER IRRIGATION NETWORK

Load curve calculation

The integrated design has the purpose to estimate the energy load curve directly linked to real irrigation needs of the farm. In this process, different aspects and possibilities are evaluated and they all could be varied with the aim to find the optimum solution, the one that specifically meets local needs.
The agricultural purpose is to entirely satisfy water needs of every crop in the fields; the irrigation system sizing method has the aim to choose the best fitting configuration that saves as much water as possible and limits the losses of the supply, while minimises the energy demand. The designing of the energy system aims to identify the most cost effective solution, considering both the necessity to meet the higher percentage of demand side and, on the other side, to decrease the net present cost of the investment. In the economic section, the analysis carried out is detailed. Considering the sizing methodology, classical methods start from a power value that has to be furnished. Hence, they consider the irrigation and the energy side separately. In the approach used in this last part of the chapter, instead, they are not independent but they condition each other, so that the decision process is not carried out systematically, but it is a sort of circle.
The first irrigation method, the traditional irrigation, is used to make comparisons with the other two energy system design approaches, the *current situation* and the *demand-driven design.*

The monthly energy peak load values or *seasonal profiles* are calculated starting from the heaviest month in the year in terms of water request. The month individuated is the one used to design the water distribution system; it is the most *water intensive.* For this reason, it is also the one that requires a higher value of energy to let the water flow. It is possible to use the software EPANET 2.0 not only to design the water distribution network, but also to evaluate the power request for the given month, assuming that pumps operate for the same period of the water distribution interval, fixed by the farmer. The most water intensive month is imposed equal to 100% of water demand. Then, after calculating the percentage of water request along one year in relation to the worst month, the same percentages are used to scale the power request in the other months of the year. In this way, the load curve is created in terms of monthly power request, considering the pump efficiency equal to 70%. This procedure is repeated for each case of the three zones, but for representation of the energy load, its cumulative for the three geographical areas, the only difference in the system size is in relation with the irrigation method chosen. To show the results in an effective way, the demand side is represented in the graph below.



GRAPH 11 ENERGY LOAD CURVES INTEGRATED DESIGN

Among the three loads calculated for the three irrigation techniques chosen, the traditional method is the one that consumes much water, but it is not always the worst in terms of energy demand. The reason is that, while sprinkler system use less water, it requires higher pressure; on the other hand, if geographical conditions are favourable, the greater pressure could be less incident and the decrease of water could led to a lower energy demand. For instance, in zone 3, where there are more crops in the first and last months of the year, the geodetic difference between pump and outlet points is favourable and it is greater than hydraulic losses inside pipes.
The inputs inserted in HOMER Pro are the same of the demand-driven design in terms of local energy resources.

To run simulations in a new way, the daily distribution could be varied in relation to the usual one, still considering the farmers' willingness not to work during the noon hours. Some other assumptions are necessary, considering that irrigation takes place not every day, but depending on the irrigation frequency adopted. Particularly, if the configuration includes a water tank, the pumping system could be oversized if the peak load remains the same. In this case, it is suggested to change the average values of load and eventually the daily load profile. These considerations on how to distribute water lead to two configurations:

1. CONFIGURATION A: every irrigation technique chosen requires a distribution network connected to a *water storage*. From the water storage, which has an adequate height, water flows by gravity and reaches all the delivery points. The pumping system could be sized on a minor peak power thanks to the possibility to fill the tank along a longer period. If the minimum irrigation frequency is equal to ten days, for instance, the pump flowrate is smaller because there are ten days to fill the tank. If the irrigation time is equal to the filling time, e.g. 7 hours, there would be only 7 hours to fill the same water tank.
2. CONFIGURATION B: the irrigation time is exactly the pumping time, so the water tank is omitted from the pumping and delivering scheme. In this way, pumps are bigger because they have to ensure a greater flowrate. The second configuration was elaborated due to high investment cost for water storage systems, but it seemed to be feasible thanks to the large availability of renewable energy sources, which permits to satisfy an even higher peak load demand than configuration A.

CONFIGURATION A

For the first configuration, the division of the field was the one elaborated before:

- Zone1, that runs along the river Mai Ainis at the southern extremity of the farm,
- Zone2, that surrounds the main house and is divided by the river from the third zone,
- Zone3 that is separated from the other areas by the river.

The possible cases to simulate with HOMER are:

- Case 1, which is the traditional irrigation method and the scheme allows also a diesel generator to supply energy;
- Case 2, pipe irrigation with renewable energy sources beside the traditional one;
- Case 3, sprinkler irrigation with renewable and hybrid plant.

Totally, there are twelve different configurations to evaluate, adding the three cumulative cases. Considering separated energy systems is due to the idea of installing three different solar pumps, which have dedicated PV panels each. On the contrary, the choice to group in only one configuration all the three zones for case one, two and three depends on the economic and management advantage derivable by one energy system instead of three smaller separate systems. Having one power station could lead to less expensive solution because of the redistribution of excess energy, or thanks to a smaller number of batteries for the battery bank. A clear example is given by Zone 1, where for the first three months there are no crops cultivated and all the energy produced by a dedicated system would be wasted. On the contrary, in cumulative solutions, there would be new investment costs for cables and energy transport in general.
The load is calculated depending on the results obtained through the EPANET water distribution network for each zone. Those results are the total dynamic heads required to irrigate fields together with the flowrates,

but considering the filling time equal to the delivery time. For this configuration, it is not necessary to install the power calculated this way, because there are water tanks that collect water during the non-irrigation days. Power values from EPANET are decreased in daily values through the irrigation frequencies. In other words, the energy request for a single month is constant and equal to a decreased value of the power derived by the software EPANET, multiplied by the sun peak hours (SPH). The SPH parameter is estimated calculating the mean daylight hours and dividing the mean value by a safety coefficient, trying to limit as much as possible the risk of a underestimated power plant , unable to meet the energy request; the result is that the energy load is distributed over four hours a day, the central ones.
Water tanks capacity is calculated through irrigation frequency and flowrate, based on the method explained in section 3.2. To minimise the water tanks cost that is the heaviest expense, the minimum capacity requested to irrigate fields is calculated for the most water intensive month. The irrigation of different crops, indeed, happens in different moments depending on their daily water needs and consumptions. A careful schedule of the irrigation actions is estimated for each crop and the maximum daily sum of all the water requests is chosen as tank capacity. Water tank cost is calculated through an average of different producers, an Italian firm Idraulica Giordano [63], a South African firm [64] and it resulted equal to around $0.3\ \frac{\$}{l}$.
The decision making process involves many considerations, such as economic aspects, but also environmental and human factors. The final choice should be convenient in all the dimensions of the sustainability: economic, social and environmental. This is why each solution should be carefully analysed under different points of view and through many sensitivity analyses.
An example of the scheme used to simulate the systems of configuration A, is reported in Figure 59. The *schematic* represents the components of the scheme, such as a diesel generator on the left, PV panels and batteries on the right, converter in the middle. Moreover, the primary load is reported on AC line. The *seasonal profile* and the *Dmap* highlight how the load changes along the months, while the daily profile shows how the load is distributed during a typical day, along four central hours. All the other load curves are reported in Appendix A.

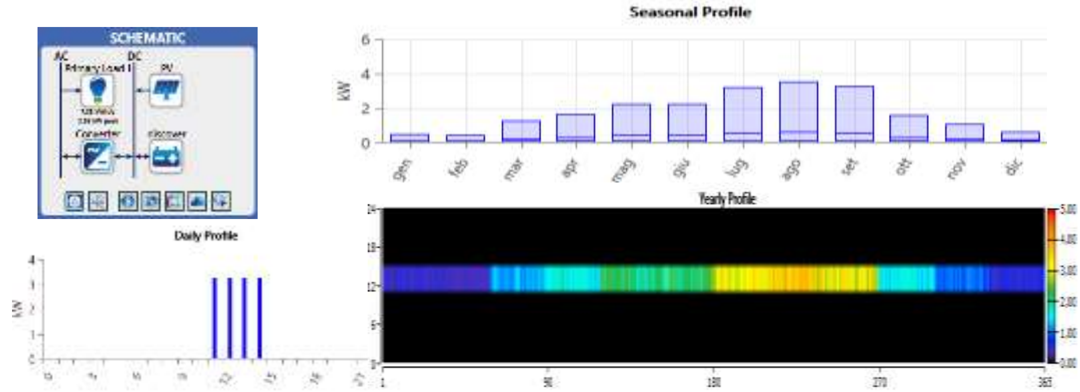


FIGURE 59 CONFIGURATION A LOW-PRESSURE PIPE IRRIGATION LOAD INPUT

CONFIGURATION B
The configuration was elaborated in order to solve the economic issue of the water tanks of Configuration A. In order to avoid the installation of big water reservoirs, with an average cost of 0.3$/l, the energy system has to distribute the water at the same time of the irrigation schedule. The peak power is greater than the previous solution, but commercial pumps have the advantage of the size effect, so the augment of the expense linked to the higher nominal power does not increase in a proportional way with the size. In this configuration, the possible alternatives are the same of configuration A, such as three zones and three different irrigation techniques each, plus the total cases in which energy is generated by only one system and it is distributed to the three zones. The energy load is calculated in EPANET and then a text file for each scheme tested was created. The file contains a demand value for each hour of the year. The text file is inserted

in HOMER Pro when it asks for the load demand as input values from external file. Power request is not daily, some days usually intercourse between two following irrigation actions. For every zone, it is calculated the amount of time in days between two irrigation actions and then it is evaluated the production/consumption of energy.

For the total cases, the load request is the sum of the single demands, keeping unvaried the days between the actions. A typical load demand is the one shown in Figure 60. The schematics include the components used for the simulations, the seasonal profile and the DMap explain how the load varies during the year on a monthly basis and the daily profile shows the distribution of the demand along one irrigation day: it is spread over the irrigation time, both in the morning and in the afternoon, but it could be distributed along a longer period. All the other load curves and HOMER inputs are reported in Appendix A.

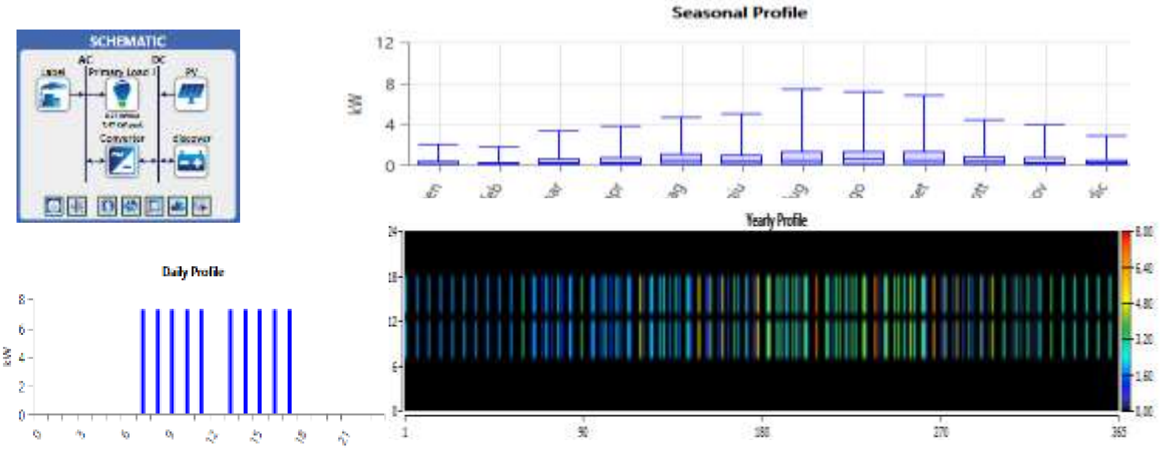


FIGURE 60 CONFIGURATION B LOW-PRESSURE PIPE IRRIGATION LOAD INPUT

4.2.4. Comparison among the results of three design methods – approach comparison

1. Load comparison

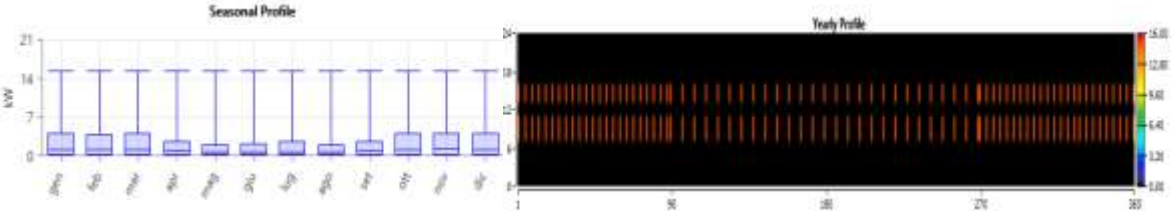


FIGURE 61 CURRENT ENERGY LOAD

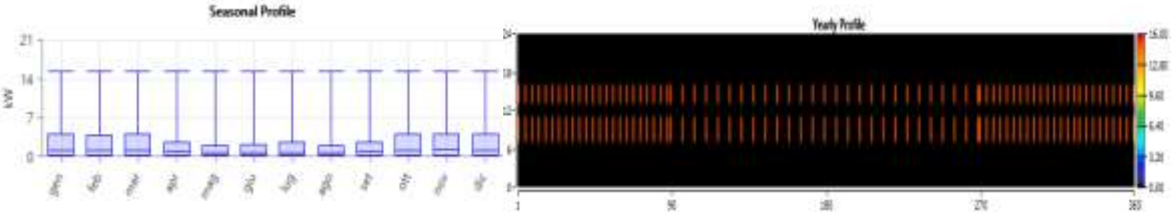


FIGURE 62 DEMAND-DRIVEN DESIGN ENERGY LOAD

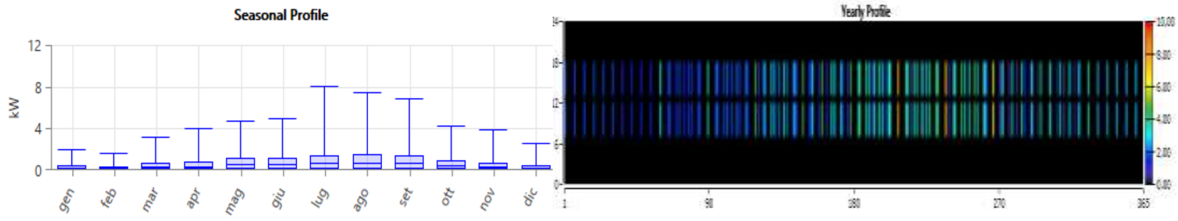


FIGURE 63 INTEGRATED DESIGN ENERGY LOAD

As it could be noticed by the figures, the load demand is completely different among the three energy system design approaches, such as the current situation load, the traditional design load, the integrated design load. For the comparison listed above, only one of the irrigation method in the integrated design is chosen and it is the traditional method in configuration B, because it is the most similar to the other two. The current situation, indeed, uses a traditional irrigation with earthen canals to distribute the water during the irrigation time, without any water tank. The traditional design has no considerations about the irrigation technique because it is focused only on the energy side, but the load curve is the same of the current situation, hence a similar irrigation method could be coupled. Then, at the end of this section, comparisons among the different cases and configurations inside the integrated design approach, the traditional irrigation, the low-pressure pipe irrigation and the sprinkler irrigation are listed. The comparisons involve the differences in the energy system configurations, economical aspects, feasibility of the solutions.
Nevertheless, clearly visible in Figure 63, the calculated energy peak value of the WEF comprehensive design is around than one half of the peak value deriving from current nominal power installed. The seasonal variability of load demand is also different, because although during the rainy season there are more natural water contribution to the fields, they are insufficient to meet the total water needs of the farm. The intensified cultivation of crops during the central months due to greater rainfalls leads to higher power request in that period. The assumptions about the expected decrease in water - and consequently in energy - demand for the rainy season were discredited by the calculations. Energy systems for the three approaches are described in Table 35 in terms of components and sizes.

	Diesel [kW]	PV [kW]	Converter [kW]	Battery (quantity)
Current situation	15	-	-	-
Demand-driven design	-	9	14	20
Integrated design	-	3	3	14

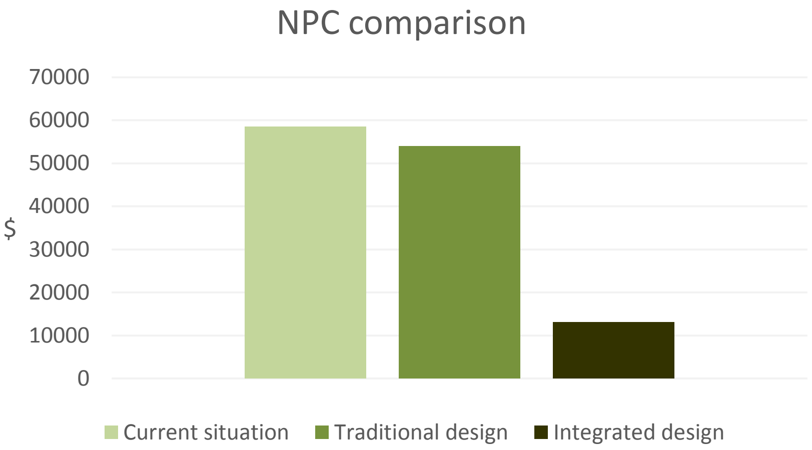
TABLE 35 COMPONENT SIZE COMPARISON

2. *Economic comparison*

The economic analysis calculates the Net Present Cost of the system components depending on their sizes, considering their replacement over the years of the project, assuming an actualisation rate k of 6%. For the sake of simplicity, this actualisation rate has been considered constant for all the project duration, while it could change as the years go by.
The NPC equation is:

$$NPC = \sum_{i=0}^{24} \frac{I_i + O\&M_i}{(1+k)^i}$$

Where I_i are the investment cost for every year and they include replacement costs when a component replacement is expected; $O\&M_i$ are the yearly operation and maintenance costs considering all the components of both the irrigation system and the energy system; k is the actualization rate.



GRAPH 12 NPC COMPARISON AMONG THREE DESIGN METHODS

Homer results show a remarkable economical difference. The analysis in Graph 12 refers only to the costs related to the energy system – without considering other costs of the irrigation system - run over the entire lifespan of the project. The value of this parameter is set to 25 years, in order to have the same terms of comparison used for renewable system that includes PV technology. The PV modules, indeed, have a lifetime of 25 years and this value is suitable for economic analyses.

The first bar represent the current situation economically simulated through a cost analysis, considering the yearly operation costs of the three diesel generators with low efficiencies. The energy and cost simulation given by HOMER Pro was not considered reliable for this case because the annual consumption of diesel expressed in litres, exceeded the admissible yearly endowment provided by the government to the farmers. Therefore, an assumption on fuel consumption was elaborated, that the farm currently consume only the quantity of diesel supplied by the government at a reduced price and the amount is equal to 160l/month at 45Nakfa/l. The cost of the fuel purchase is then actualised for 25 years and the sum is the NPC of the current situation simulation. The second bar represents the energy system configuration elaborated through the demand-driven design method, hence with the same load curve of the current energy consumption. Using renewable sources that have negligible operating costs, the NPC has a lower level, but not significantly different because of the high nominal power of the energy plant. The last bar is the NPC obtained through the simulation of the power generation configuration. In this case, the load is the one obtained with the integrated design and the peak power installed is remarkably lower, as the NPC is.

Considering now the obtainable revenues as the avoided cost of buying diesel to power the motor pumps, and the total yearly investment cost including both energy and irrigation system, it is possible to evaluate the Net Cash Flow for every year and to calculate the pay back time of the eventual energy system configuration elaborated through the integrated design approach. The formula used to calculate the Net Present Value, or the sum of actualised yearly Net Cash Flow is:

$$NPV = \sum_{i=0}^{24} \frac{R_I - (I_i + O\&M_i)}{(1+k)^i}$$

The revenues R_I not include the expected enhancement in crop yield because there were no data available for a baseline. Behind the estimations made by the farmers, which were statistically unreliable, there were

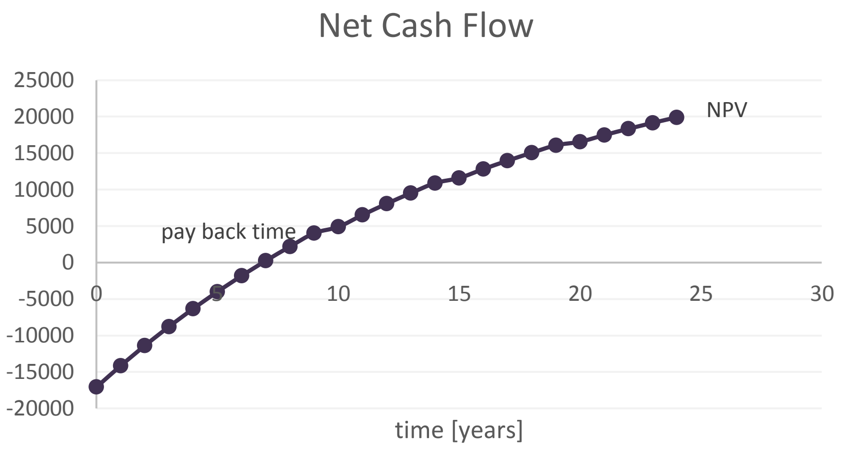
no documents or contracts in which were defined the conditions of sale. During the field experience, an excel file to manage production and revenues was developed together with the farmers. It was created with the aim of producing analysis about production trends, even if there was not a baseline.
I_i are the investment costs for year i, considering both investments and components replacement whenever their lifetime is over. In Table 36 are resumed the main inputs required for the NCF calculation, some of them are estimated through HOMER Pro simulations, some other are manually calculated:

	Investment [$]	O&M [$/yr]	Replacement time
Pumps	1100		8 years
PV	6000	25	25 years
Battery	3220	10	15 years
Converter	2100	10	15 years
Pipes	3200		Not available
Land maintenance		1080	-
Electric accessories	1400	-	13 years

TABLE 36 ECONOMIC ANALYSIS INPUTS

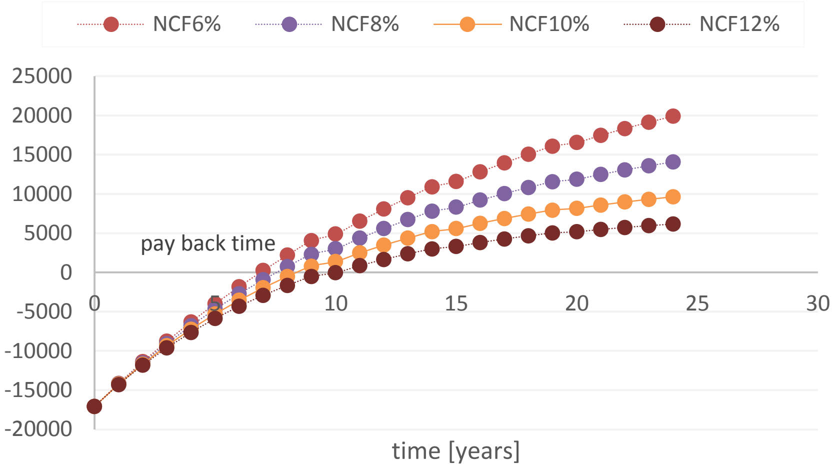
Pipe replacement time is not available because there were no information about how frequently pipes were substituted (due to possible damages caused by animals). They were excluded by the economic analysis in terms of their replacement cost, on the contrary they were considered as an investment cost at the beginning of the project. The impact of land preparation is another important parameter. For the traditional irrigation technique - the one chosen for comparisons- the number of necessary workers should be estimated, their weekly maintenance time dedicated to land, the yearly operation required after ploughing fields and their salary. For earthen canals distribution system, the assumptions are to count for one entire week for the realisation of the canals made by 2 workers twice a year (ploughing fields occurs twice in a year); ordinary maintenance of 4 hours a week during the non-rainy season (36 weeks a year), made by one worker; maintenance of 3 days a week during the rainy season (15 weeks a year), all actualised in 25 years because it was assumed as project lifetime. All these information derive from farmers' evaluations.

In the graph below, yearly cumulative NCF is plotted over time, in order to estimate the pay-back time of the investment. It is around 5 years, while the NPV is around 20000$, for an initial investment of 18000$.



GRAPH 13 NCF INTEGRATED DESIGN ENERGY AND IRRIGATION SYSTEM

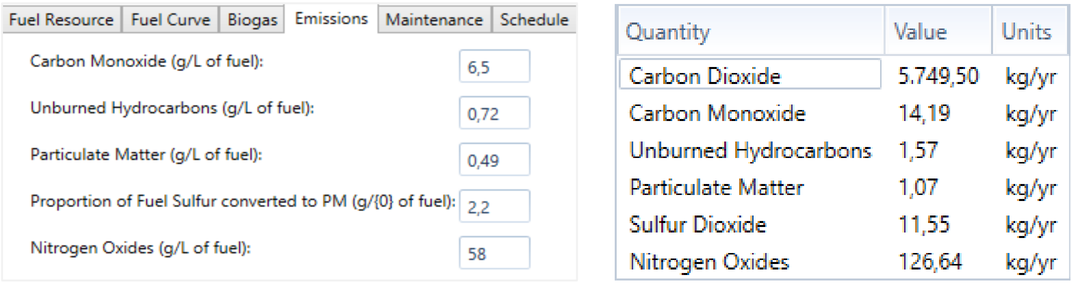
Different actualisation rate were considered to evaluate how they could affect the economic results. The actualisation rate is linked to inflation rate and in developing countries, it could suddenly change. To have the general picture of the possibilities that the implementation could face, the actualisation rate was incremented from 6% to 12%, as shown in Graph 14. The differences in pay back time are not very considerable, even if the rate doubles its original value. The NPV instead decrease until one quarter due to the long term of the analysis, 25 years, and because the forecast along such an extended period is less accurate.



GRAPH 14 NCF VARYING WITH ACTUALISATION RATE

3. *Emission comparison*

The reported emissions refer to the only case including diesel consumption, the current situation case. The diesel consumption is limited to 160l/month because it is the amount of fuel permitted by the government for the Ferrando Ezechiele agricultural farm. HOMER information on general diesel were used to assess yearly emissions of carbon dioxide, carbon dioxide, unburned hydrocarbons, particulate matter, sulphur dioxide and nitrogen oxides. The other two cases use renewable sources, hence yearly emissions are equal to zero.



Carbon Monoxide (g/L of fuel): 6,5
Unburned Hydrocarbons (g/L of fuel): 0,72
Particulate Matter (g/L of fuel): 0,49
Proportion of Fuel Sulfur converted to PM (g/{0} of fuel): 2,2
Nitrogen Oxides (g/L of fuel): 58

Quantity	Value	Units
Carbon Dioxide	5.749,50	kg/yr
Carbon Monoxide	14,19	kg/yr
Unburned Hydrocarbons	1,57	kg/yr
Particulate Matter	1,07	kg/yr
Sulfur Dioxide	11,55	kg/yr
Nitrogen Oxides	126,64	kg/yr

TABLE 37 EMISSIONS-CURRENT SITUATION

4.2.5. Results and comparison in the integrated water-energy system design – technological comparison

The integrated design of the energy and irrigation system shows a huge potential in decreasing energy and water consumption, using only the necessary sources and minimising waste. Inside this approach, three irrigation techniques and their relative systems are analysed, considering two configurations, A and B, to pump and collect water for irrigation. Hereafter the results of the energy simulations are compared and an economic analysis is carried out with both components of the energy system and of the irrigation system. For the best solution or the one that minimalizes the economical effort, other considerations on components costs are evaluated to clarify which one is the most cost-effective.

The results show that although the configuration A allows choosing smaller pumps and consequently smaller power system installed, the water tank cost impact is heavy enough to make unfeasible this system setup. Moreover, while HOMER Pro simulates only the energy system, there are many other components of the systems analysed that have to be considered in an economic evaluation. Considering a lifespan of 25 years, the components that should be introduced in the analysis are pumps, which could last for an average of 8-10 years for an irrigation application like the ones of interest; pipes that are affected to frequent maintenance and substitutions, electric accessories such as control unit, DC cables, plug connectors, junction box, solar panel structure, earth rods, earth wire. Their prices are mainly obtained through producers' price-lists. Finally, sprinklers have to be accounted for the third case assessments. The impact of land preparation is another important parameter. Depending on the irrigation technique chosen, the number of requested workers should be estimated, their weekly maintenance time dedicated to land, the yearly operation required after ploughing fields and their salary. For earthen canals distribution system, the assumptions are the same of the previous sub section. In case of low-pressure pipe system, the required operation are the ones in correspondence of the ploughing periods, moving pipes and replacing them. Time required is the same both times and it is 2 days a week twice a year. In the sprinkler system, as in pipe system, there is little land preparation. Workers' hourly or daily salary was estimated through the survey that was filled by the farmers, considering the average exchange currency rate of past years to obtain the labour cost in US$.

Because there were no information about how frequently pipes were substituted, they were excluded by the economic analysis in terms of their replacement cost, on the contrary they were considered as an investment cost, because they have different values for pipe system irrigation (high pipe use) and traditional irrigation method (very low pipe use).

The economic analysis is a cost analysis, because data about yearly revenues were incomplete. Possible estimation of revenues should include all the avoided costs in relation to the current expenses, but also incremented revenues by higher selling activities. The first part could be estimated as avoided cost of diesel fuel and avoided or reduced land maintenance cost. For the second a baseline data was not available and consequently it was not possible to estimate a reasonable increment of the revenues by agricultural products selling.

The economic analysis calculates the net present cost depending on components and sizes, during all the years of the project, assuming an actualisation rate k of 6%.

	Investment cost [$]	O&M [$/yr]	Replacement time
Land maintenance		1080[6]/215[7]	-
Electric accessories [$]	1400[8]/1000[9]	-	13 years
Water tank [$/l]	0.3	30	40 years
Sprinkler [$/unit]	51		15 years

TABLE 38 COST ITEMS

Pump price is obtained from producers price-lists choosing the specific pump in correspondence of the most similar pump size (head and flowrate) evaluated for each configuration. The same method is applied to calculate pipes investment cost. When the diameters of every pipes are optimised through EPANET during the design of the water distribution network, they are compared to commercial pipe diameters, whose price are known in [$/m]. Pipe price does not increment linearly with diameter, so there is not a single price per meter.

---

[6] For traditional irrigation method

[7] For low-pressure pipe irrigation and sprinkler irrigation

[8] Cumulative energy systems

[9] Dedicated energy system (cost per one single energy system)

CONFIGURATION A

Energy systems set-ups for configuration A show low installed peak power because water tanks allow decreasing the power demand. Net present Cost is calculated and reported for each simulation, considering both the energy system and the irrigation system. Only the cumulative solutions are listed in Table 39 because of their economical and technical feasibility.

For both configurations, the energy system includes:

- Energy plant components
- Electric accessories

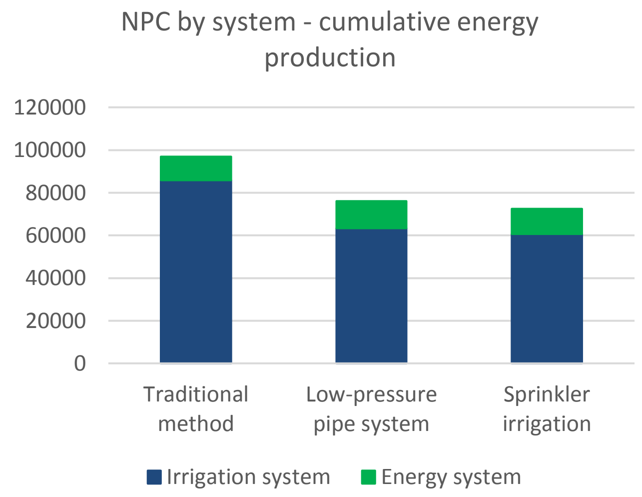
While the irrigation system includes:

- Electric pumps
- Pipes
- Land preparation
- Water tank (if used)
- Sprinklers (if used)

	Diesel kW	Batteries quantity	Converter kw	PV kW
Cumulative, traditional method	-	5	2	2.2
Cumulative, low-pressure	-	6	2.5	2.5
Cumulative, sprinkler irrigation	-	5	2	2.5

TABLE 39 ENERGY SYSTEMS SIZES BY COMPONENTS

The best solution in terms of economic advantage is the sprinkler irrigation, although there is no remarkable difference with low-pressure pipe irrigation. The irrigation system is by far the most significant voice of the total cost and it is mainly due to water tank cost. If smaller water tanks are chosen, in order to reduce the investment cost of this component, the water supply to crops is not guaranteed in the exact moment when they need it. Because matching the real water needs with an adequate energy production system linked to the irrigation technique used is the purpose of this design approach, the solution of smaller water tanks is not considered.

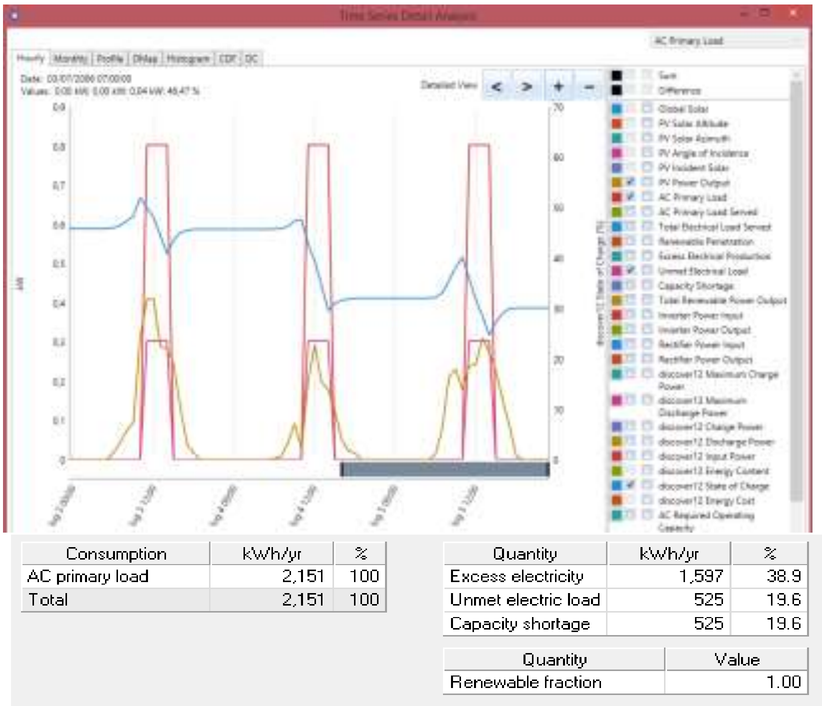


GRAPH 15

There is no remarkable difference between installing one single energy system and three separated systems, but having only one energy plant could be easier to maintain or to control in order to avoid thefts. The HOMER Pro results for the cumulative solutions show a better energy production to consumption ratio than the separated ones, because the water request during one year could be remarkably variable. For instance, in Zone 1 there are no crops during January, February and March. The energy production would be completely lost if Zone 1 had a dedicated energy plant. Even with cumulated solutions, some energy is produced but not consumed, but it depends on crops cultivation and their variable water needs along the years.

In the figure below, there are results about configuration A in terms of PV power production, battery state of charge (SOC), load served or load demand and unmet load. Power production by PV panels is in series with batteries during non-irrigation days, and in parallel with energy supplied by batteries, during irrigation actions. As it is shown in the figure, during the months with higher energy demand, a fraction of load is unmet, in the last hour of the load profile. In the boxes the results of production, consumption and excess electricity is reported. The values of excess electricity is around 30% because crop production and cultivation is not constant during the year. During the first three months of the year, for instance, in zone 1 there are no crops at all. For this reason, the energy production, which on the contrary is quite uniform during the year, would be partly wasted. The cumulative cases are more suitable to decrease the excess energy than separated energy systems, because the energy produced during the months with lesser load for one zone, could be reused in the other two zones.

The load is almost similar for everyday, the only changing thing is the monthly average load value. It is clear from the figure that the water tank permit to meet the energy demand more uniformly during the year, with only 16% unmet load for the simulation of cumulative energy system low-pressure pipe irrigation Figure 64.



Consumption	kWh/yr	%
AC primary load	2,151	100
Total	2,151	100

Quantity	kWh/yr	%
Excess electricity	1,597	38.9
Unmet electric load	525	19.6
Capacity shortage	525	19.6

Quantity	Value
Renewable fraction	1.00

FIGURE 64 LOW-PRESSURE PIPE IRRIGATION HOMER PRO RESULTS

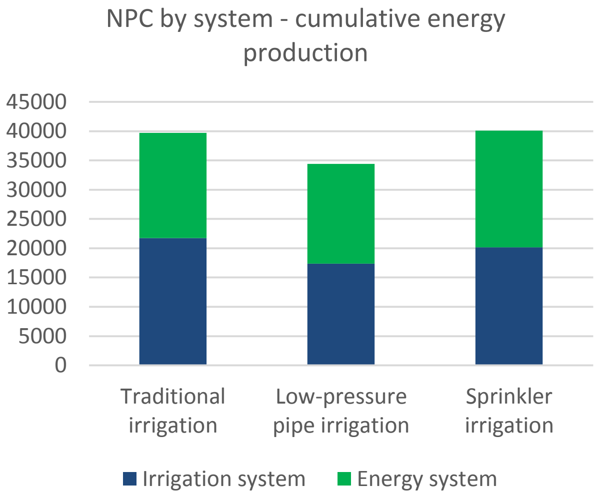
CONFIGURATION B

In the second configuration, the load is distributed in a different way because there are no water tanks. A greater number of batteries are used because the energy supply during an irrigation day is concentrated in the delivery time, that is no more 7 hours, as in the other cases, but its value is increased. The reason is that the new system does not require hand labour to work. Batteries and PV panels operate in parallel to supply the required energy to the pumps, while in configuration A the process is mainly in series between pumps and water tanks: PV panels supply energy to pumps that fill the water tanks that are emptied during the irrigation action, although the system could also operate in parallel, filling the tanks during the irrigation actions.

	Diesel kW	Batteries quantity	Converter kw	PV kW
Cumulative, traditional method	-	14	3.5	3
Cumulative, low-pressure	-	14	3	3
Cumulative, sprinkler irrigation	-	14	3	4

TABLE 40 SYSTEMS SIZES BY COMPONENTS AND ZONES

Net Present Cost is calculated as in configuration A and the graph below report the totals divided by irrigation techniques.
This time, the totals are strongly different from the previous configuration. The increase in peak power installed and consequently in investment cost related to energy system components, has not the same impact of the avoided cost of water tanks.



GRAPH 16

The results are different if compared with configuration A, it is clear there is one less investment cost, the one related to water tanks. On the other hand, the differences among the three cases are not as remarkable as in configuration A, where traditional irrigation was by far the most expensive; on the contrary, sprinkler irrigation seems as expensive as traditional irrigation method. The economic analysis, nevertheless, do not consider the water saving as a revenue because if there is water shortage, water is not bought to irrigate due to its unaffordability. The risk factor of using a higher amount of water in traditional irrigation in relation to the other two methods is not modelled. The advantage of having one single system that produces energy, instead of three dedicated systems, derives by the better and deeper use of the solar resource. In the graphs below, the charging/discharging process could be noticed. It is possible to understand the energy demand distribution. The load curve is calculated separately for each crop depending on its water needs and its irrigation frequency. Then, a yearly load curve is calculated as the sum of every crop load, for every hour of the year, considering their planting date and growing period.

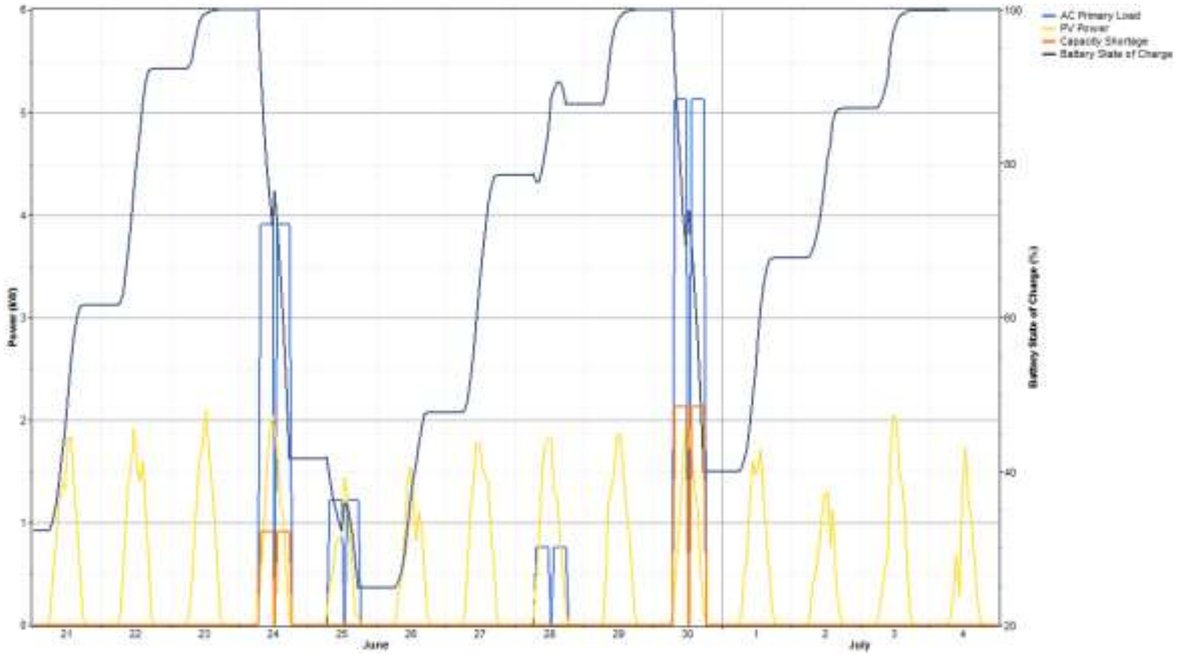


FIGURE 65 LOW-PRESSURE PIPE IRRIGATION HOMER PRO RESULTS

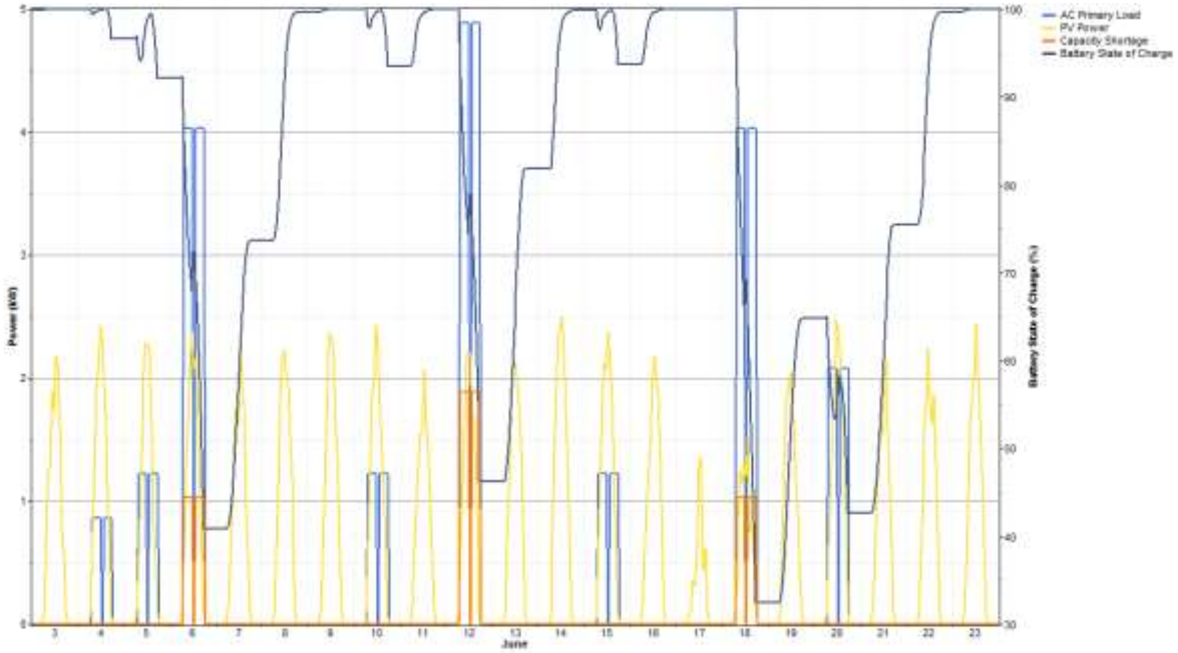


FIGURE 66 SPRINKLER IRRIGATION HOMER PRO RESULTS

In order to understand the economic feasibility of the solution suggested, a sensitivity analysis was fulfilled. The sensitivity variable is the capacity shortage, decreased from 20% up to 10%; the observed variable is the total Net Present Cost. In the following graphs, the results are plotted to clarify the unaffordability that a lower capacity shortage would cause. The capacity shortage limit remains the original value equal to 20%.

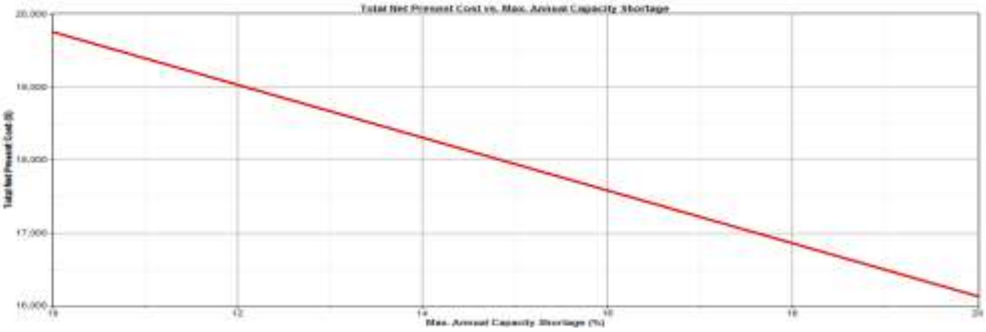


FIGURE 67 ENERGY SYSTEM NPC VS CAPACITY SHORTAGE, TRADITIONAL IRRIGATION

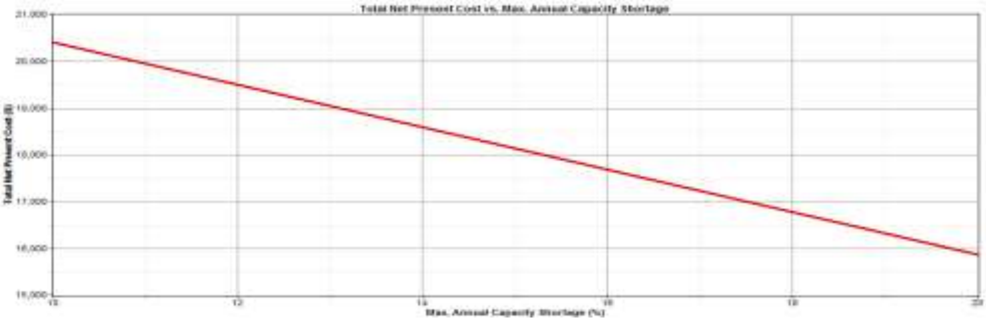


FIGURE 68 ENERGY SYSTEM NPC VS CAPACITY SHORTAGE, LOW-PRESSURE PIPE IRRIGATION

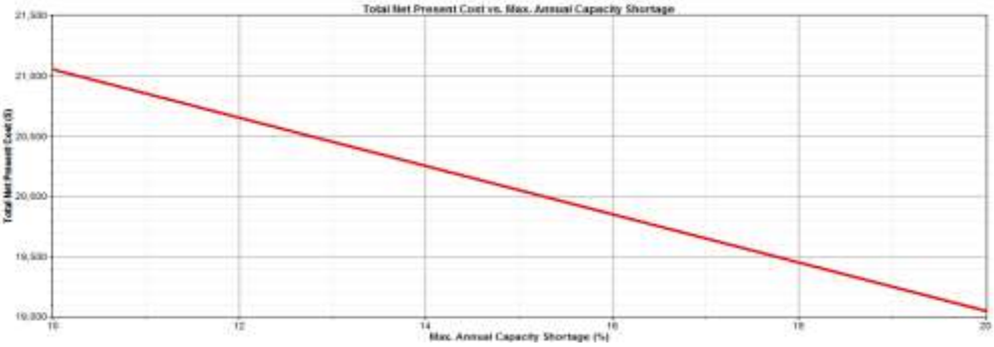
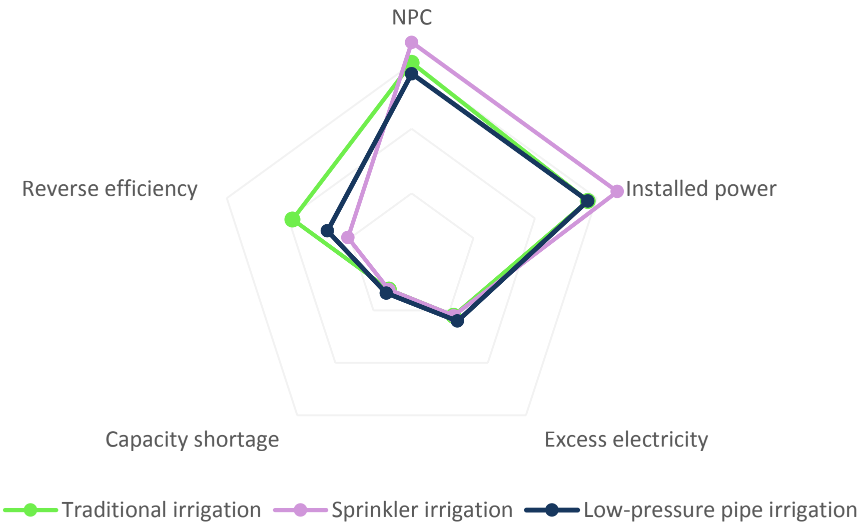


FIGURE 69 ENERGY SYSTEM NPC VS CAPACITY SHORTAGE, SPRINKLER IRRIGATION

The most advantageous solution is the low-pressure pipe system, with a NPC in 25 years of around 35000$. The choice derives from a panel of indicators, such as the NPC of the energy and irrigation system, the irrigation efficiency, the unmet load, the installed power, the excess electricity. In order to evaluate the advantages of each solution in a comprehensive way, Graph 17 shows the values for each indicator. They are all expressed as percentages in order to better visualise the differences. Because all the values except from the irrigation efficiency are worse if they increment, the efficiencies of the three systems are expressed as reverse efficiencies ($(1-\eta)$). A smaller area represent a better investment. For sprinkler irrigation, reverse efficiency of the irrigation method is better than low-pressure pipe irrigation, while NPC values are the opposite. The low-pressure pipe irrigation has a slightly better percentage of unmet load is while the excess electricity and the installed power are the same of the sprinkler irrigation.

Since the economic factor could have higher impact, the low-pressure pipe irrigation and energy system is used to further explore its components weight on the total NPC in the following paragraph.



GRAPH 17 SPIDER GRAPH OF THE THREE CUMULATIVE SOLUTIONS - CONFIGURATION B

Economic analysis of the components – low-pressure irrigation energy and water system

Other economic analyses were made in order to understand how components costs affect the total NPC. To do these comparisons, the less expensive configuration was considered, the cumulated case -configuration B, with an admitted unmet load of 20%. The economic sensitive analyses start with a baseline of costs given by the information contained in the scientific paper [54], varying pumps cost, photovoltaic cost, converter cost and battery cost and technology. The constant costs were the electric accessories costs and land preparation cost, which are not expected to be changing. Pipes cost is not included in the comparisons because their lifespan is strongly uncertain to forecast. For each component whose price is subjected to a sensitive analysis, its NPC is calculated on 25 years and it is evaluated the percentage weight it has in relation to the others factors.

Pumps price are derived from three different firms, one Italian (Idraulica Giordano [63]) with higher expense due to shipping costs, a British owned company – SALFLO Pumps - with two branches in South Africa [65], a multinational originally Indian company – C.R.I. water pumps [66]. Pumps are supposed to last for at least 8 years and considering the lifetime of the project (25 years), they are supposed to be replaced three times. Because of the low nominal power of the requested pumps, they could be very cheap so their impact on the overall NPC could be lower than 10%. Size effect advantage is not used, because even in cumulated cases like the one in analysis, it is preferable to have separated pumps dedicated to different zones of the farm. The choice allows the farmers to distribute water only in the interested areas, without a complex management of valves and devices to divert the water flow.

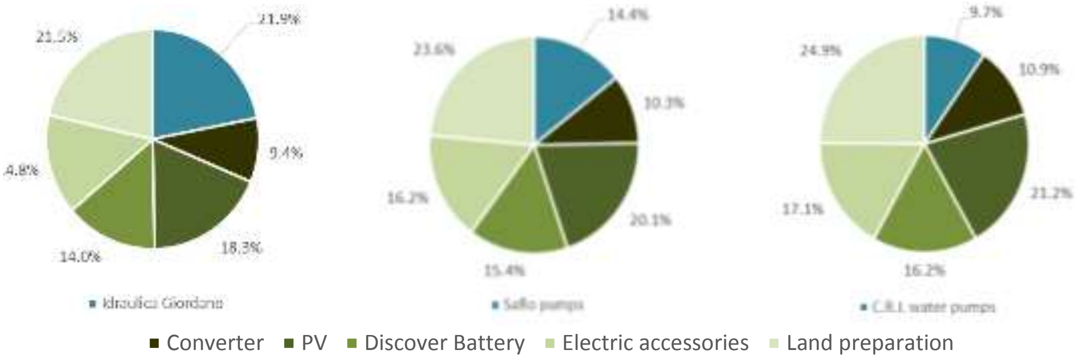


FIGURE 70 PUMP NPC VARIABILITY

The different solar PV panel prices were obtained through ENF Solar [67], a website that collects producers, sellers and installers linked to the solar industry. Behind the original price of Ethiopian market, the panels compared are produced in Spain and China, but the Spanish one is already sold in Kenya. The panel are not expected to be substituted during the whole period evaluated, such as their lifespan is equal to the project lifetime. Ethiopian PV panels price is greater than Spain panels and Chinese ones probably because of different market drivers and different availability of resources and technological levels. Nevertheless, in a few years the situation could change, if African countries would be “catching up” by growing faster than developed countries. Developing countries would leapfrog over some earlier stages of technological development, using for instance new production line in renewable energy exploitation technologies, such as PV panels, decreasing in price and aligning to European market price is a real possibility [4].

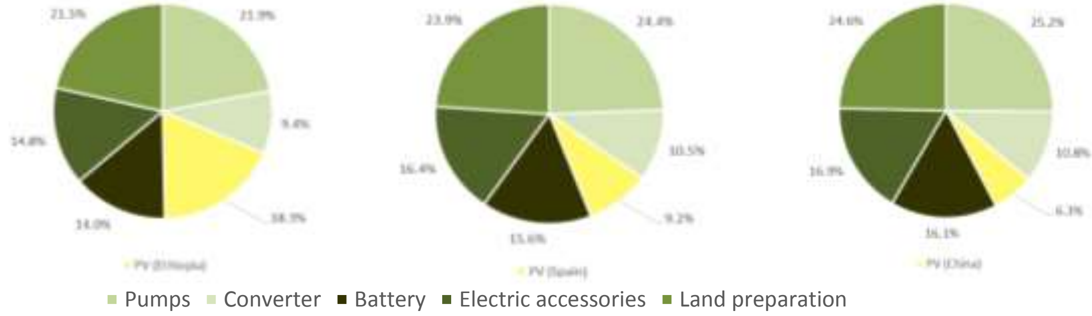


FIGURE 71 PV NPC VARIABILITY

Converter prices are collected from producers websites, but there were no significant differences in costs. Considering its lifespan, converter is replaced once along the 25years project. Its impact on total NPC varies only from 9% to around 5%, as shown Figure 72.

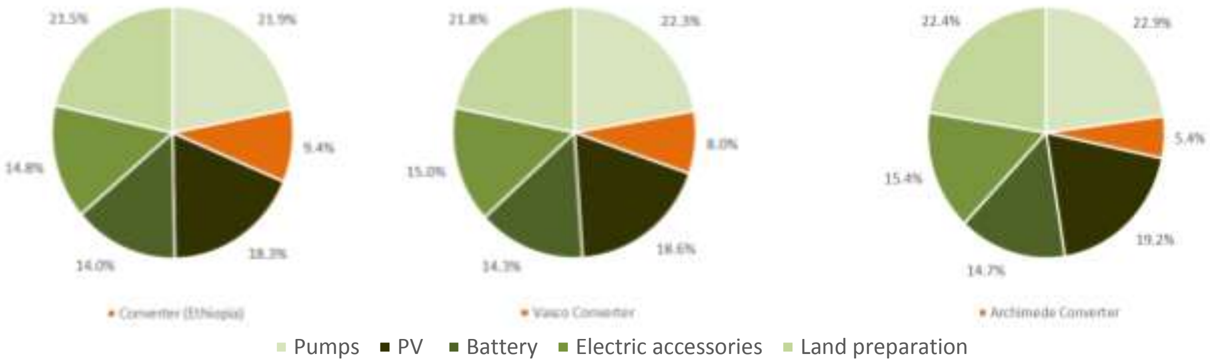


FIGURE 72 CONVERTER NPC VARIABILITY

Batteries are an important component, because in the case analysed there are not water tanks and energy must be supplied directly during the irrigation action. Because PV panels cannot reach the peak value of the power request, batteries supplies energy in parallel with PV system in configuration B, which is the one explored in these components analyses. In this last analysis, the difference of battery price is considered asmong time, thanks to a price forecast estimated by the International Renewable Energy Agency [68]. According to the reasearch, in 2017 lithium-ion batteries would be the cheapest technology, followed by sodium metal halide, sodium sulphur and advanced lead-acid batteries. With this expected decrease in cost and its higher performances, lithium-ion battery would lead to a reduction in NPC by one half (Figure 73). The study shows that the decreasing cost trend continues also in 2020, where lithium-ion batteries would cost one third of their price in 2017. If this forecast is reliable, using this technology would became in ablosute the best choice for a renewable stand alone system.

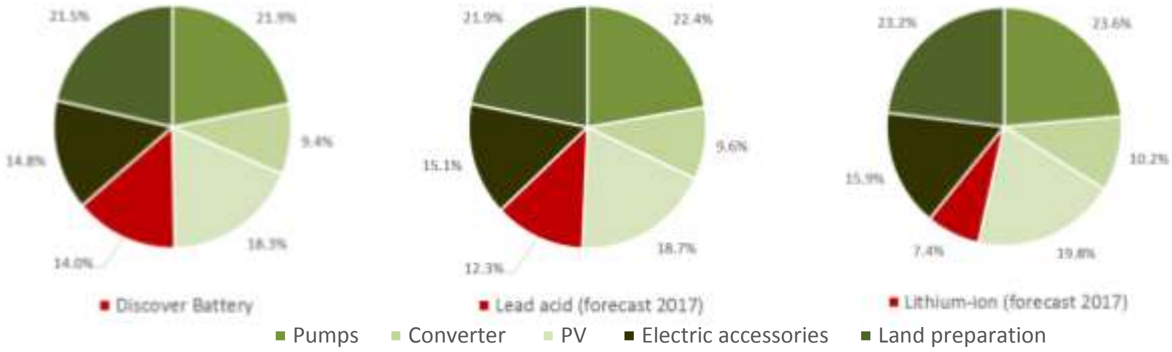


FIGURE 73 BATTERY NPC VARIABILITY

Finally, pumps cost is a heavy component for the NPC of the project because they the components with lower lifespan (only 8 years). Moreover, small pumps in terms of nominal power, costs much in $/kW tan bigger pumps. In the situation analyses, there are three pumps, while a single pump with lower cost per kW installed could be sufficient. PV panel cost is a remarkable part of NPC, but it is mostly due to local market constraints and the price is likely to decrease in time, as it happened in Europe during the last years and because they are tested technologies. For the battery share of NPC, on the contrary, the analyses is based on a forecast about Developed Countries' markets. Probably, a longer time would be required in Eritrea to reach the decrease in NPC percentage calculated.

Chapter 5 CONCLUSIONS

The thesis reached a great achievement in its case study, the large awareness of the importance of a correct energy and water management, in a region where energy and water are becoming threatening issues. Energy inefficiencies are unsustainable both for the environment, which is strongly affected by degradation and in terms of economic feasibility. Water waste is not acceptable when its availability is limited to few months a year. A good practice could be considered as an example for other farmers suffering the same difficulties. It could lead to a general enhancement of the resources of the region and to economic benefits for the entire community living in the same area and sharing the same resources.

Several conceptual frameworks have been proposed to guide efforts that could increase potential yields in farms mostly in developing countries, while at the same time they should reduce environmental consequences of intensive agriculture. These frameworks include “ecological intensification” and “evergreen revolution” [15] [16] [17]; they share a view of cropping systems as ecosystems that should be designed to make maximum use of fixed resources (land and favourable growing conditions) and optimum use of agricultural inputs (water, fertilizer, and other chemicals) to produce useful products. Such systems can draw upon features of traditional agricultural knowledge and add new ecological information into the intensification process. Although there is agreement on the need for such improvements, there are few examples of how they can be developed and adapted across hundreds of millions of farmers’ fields [19].

The strength of this thesis is the feasibility of the integrated design approach and its conceptual adaptability to every situation. The entire development of a project aimed to supply energy for irrigation systems is changed and it relies on the study of local resources interconnections, using what is locally available in a sustainable way.

To clarify the flexibility of the integrated approach design, it is described in a general way. In an irrigation system in rural areas of developing countries both the water and the energy point of views should be observed through:

1. Local Water resources
2. Water needs of local agricultural products
3. Irrigation techniques applied
4. Load curve calculation, local energy resources and possible exploitation technologies

Passing through this four interconnected steps leads to create a global vision about real crop water needs, about how irrigation affects those water needs and how they are translated in energy request. All the assumption and choices are made considering related costs and the technical feasibility of solutions, the involvement of locals, the human empowerment the new approach could bring, the environmental protection. Farmer awareness about communal water management and effective crop water requirements are the milestones in the development of the work presented. Very often, in developing countries traditional behaviours resist to change, mainly because of low information diffusion. Developing a new model is requested in order to implement successful solutions that locals would use on the long run. The feasibility of a project takes into consideration the socio-cultural texture of the interested area, especially to ensure long-term viability. There are skills that have to be enforced, some others to be created, risks to overcome, both economic and political ones.

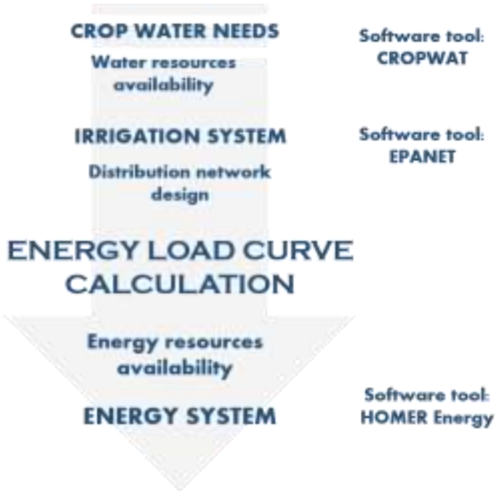


FIGURE 74 THE INTEGRATED DESIGN APPROACH LOGICAL DIAGRAM

Inside the integrated design suggested and used in this thesis, at the end of the observation and calculation phases, results will be the real energy load curve and the most suitable energy system to meet that curve. It derives from a sequence of stages, starting with the analyses of water resources availability in order to know the *local* water endowment. The study continues calculating the appropriate amount of water required by a crop or by a crop pattern. Then, an irrigation technique is selected and the water distribution network is elaborated; the energy load curve is calculated through all the information hitherto collected. At the end, the energy system is sized considering the availability of local energy resources. The decision making process will compare solutions with the related advantages and disadvantages, considering all the affecting parameters and the stakeholders that are interested in the project. A possible structure to arrange the integrated approach is explained in Figure 74.

- *Local Water resources*

Assessments about national water resources could be locally carried out, collecting data about water sources for a valuable number of year in order to avoid seasonal variability errors. Water statistics exist and they are elaborated over decades by international organisation, such as FAO. Water resources are usually divided into renewable, non-renewable, such as groundwater bodies that have a negligible rate of recharge on the human time-scale, internal renewable water resources (IRWR), both surface water and groundwater, generated from endogenous precipitation, and finally external renewable water resources (ERWR), which is water entering from upstream countries through rivers or aquifers. ERWR include also the resources of shared lakes or border rivers.
In order to quantify how water assessments are carried out and which parameters affect the most the water endowment of a region, two indicators are introduced and described, the Internal Renewable Water Resource and the External Renewable Water Resource. FAO elaborated a method to compute the evaluation, available at [2]. According to the paper, assessing the internal renewable water resources by country can be done by calculating:

$$IRWR = R + I - (Q_{OUT} - Q_{IN})$$

Where:
$R =$ surface runoff, which is the total volume of the long-term average annual flow of surface water generated by direct runoff from endogenous precipitation;
$I =$ groundwater recharge, generated from precipitation within the country;
$Q_{OUT} =$ groundwater drainage into rivers (typically, base flow of rivers);

Q_{IN} = seepage from rivers into aquifers;
$Q_{OUT} - Q_{IN}$ is also called overlap.

In semi-arid areas IRWR are generated mainly from flash-flood events. Groundwater resources are obtained from rainfall infiltration estimates or from measurements of groundwater level/heads in aquifers. The surface water resources are estimated through flash-flood discharge measurements or estimates. In very arid areas, as coastal ones, a large part of the groundwater aquifers is not drained by the rivers and overlap is therefore relatively small. In general, in almost all countries a part of IRWR has to be estimated by models using rainfall data, considering the hydro-climatological context while choosing the model.
For what concerns ERWR, the assessment goes through the calculation:

$$ERWR = SW_{IN} + SW_{PR} + SW_{PL} + SW_{OUT} + GW_{IN}$$

Where:
SW_{IN} = surface water entering the country;
SW_{PR} = accounted flow of border rivers;
SW_{PL} = accounted part of shared lakes;
SW_{OUT} = volume of surface water leaving the country which is reserved by treaties for downstream countries;
GW_{IN} = groundwater entering the country.

The mean annual flow measured or estimated at the border of a transboundary river SW_{IN} is accounted for as an external resource for the downstream country. SW_{PR} follows the general rule that splits the river flow in two equal parts assigning one half to each of the bordering countries. The mean annual estimated groundwater flow entering the country GW_{IN} is accounted for as an external resource, while computation does not consider outflow of groundwater (GW_{OUT}).
In case of absence of data about total renewable water resources, it would be useful to carry on tests on the extraction points. As an example, if water is withdrawn from a surface resource, the water flow value should be collected during a reliable period of time, in order to avoid seasonal variability. If water comes from a well, it is suggested to do a pump test to find how much time is required to refill the water, or how much water the well is able to extract. This value is not equal to the pump nominal flowrate and it depends on local utilise and local factors, for instance well depth. Nevertheless, each situation has its own characteristics and tests or calculations should be evaluated in relation with local context. The purpose is to find the value of available water for irrigation in $\left[\frac{l}{s}\right]$. Then, after the calculation of crop water needs in the following steps, the crop water requirement would be known in $\left[\frac{l}{s \cdot ha}\right]$. Though the ratio between available water and crop water requirement, the surface that could be sustainably and efficiently cultivated is obtained in $[ha]$.

- *Water needs of local agricultural products*

In this step water needs of locally cultivated products are calculated starting with local data about climatic conditions, soil and crop type. To evaluate water needs in the case study an open source decision support system elaborated by FAO, CROPWAT, is used. Any other similar available tool able to identify the water requirements of agricultural products could be used, the required inputs are always the same: climate, soil, crop type.
CROPWAT calculates crop water requirement (CWR), i.e. the quantity of water needed by a specific crop; net scheme irrigation supply (NSIS), an average of the water needs of a crop pattern, weighted on the percentage of cropped areas; and the scheduling of the water supply. Those outputs make the user aware of the correct and sustainable water use. In order to use CROPWAT, or a similar software tool, the user have to collect some data about the environment in which the crops are cultivated.
For the climate data, they can be derived by local measurements - as the other data - or through a database, CLIMWAT [69]. CLIMWAT provides monthly mean values of the seven climatic parameters required by CROPWAT.

They concern clime, rain, crop type, soil.:

- Mean daily maximum temperature in °C
- Mean daily minimum temperature in °C
- Mean relative humidity in %
- Mean wind speed in km/day
- Mean sunshine hours per day
- Monthly rainfall in mm/month
- Monthly effective rainfall in mm/month

Reference evapotranspiration calculated with the Penman-Monteith method in mm/day and Mean solar radiation in MJ/m2/day are the two parameters calculated thanks to the seven values listed (for a complete discussion see Chapter 3).

These parameters and the others about soil and crop type, are fundamental to evaluate the potential of the arable land and they allow to know how much of the water needs could be reached without any intervention (rain fed production). If climate and rainfall are enough, no extra water is required. On the contrary, if weather trend is not satisfactory, the lack of water has to be balanced out through an appropriate irrigation schedule. The fact is that water needs are strictly linked with the irrigation method used, because of the effectiveness of the system, the capacity of the soil not to drain water, the general efficiency of the water distribution network. The software CROPWAT, after calculating the net water requirement for every crop analysed, accounts for the linkage with the irrigation method asking a percentage of efficiency of the irrigation system. It is defined as the ratio between the net water need of a crop (or more than one crop) and the water effectively supplied, including conveyance and field losses. Nevertheless, using a different tool that has not a link with irrigation would not be a constraint: irrigation efficiency can be considered in the next step.

- *Irrigation technique applied*

The suitability of the various irrigation methods, that can be rearranged in three main techniques, i.e. surface, sprinkler or drip irrigation [43], depends mainly on natural conditions, type of crop, type of technology, previous experience with irrigation, required labour inputs, costs and benefits.

The natural conditions such as soil type, slope, climate, water quality and availability, could have different impacts on the choice of an irrigation method. As explained in Chapter 4, and practically applied in the decision process about the irrigation techniques to consider in the case study, soil is the main variable affecting the quality of an irrigation method. For instance, sandy soils can store less water because of their high infiltration rate, that favourites water losses by deep percolation. They therefore need frequent but small irrigation applications. Under these circumstances, sprinkler or drip irrigation are more suitable than surface irrigation. On loamy or clay soils, all three irrigation methods can be used. Clay soils with low infiltration rates are ideally suited to surface irrigation, because deep percolation losses are the minimal. If the crop requires a uniform distribution, sprinkler or drip irrigation are recommended, as they will ensure a more homogeneous water spread. Sprinkler or drip irrigation are preferred above surface irrigation on steeper or unevenly sloping lands as they require little or no land levelling. An exception is rice grown on terraces on sloping lands, because rice generally needs surface irrigation, even if something is changing right now. In Israel, new techniques are being tested such as drip irrigation for rice crops, due to the national water scarcity [70].

Also the climatic parameters affect the choice of irrigation technique, for instance strong wind can disturb the spraying of water from sprinklers. In windy conditions, drip or surface irrigation methods are preferred, but wind could lead to higher evaporation rates in surface irrigation. In areas of supplementary irrigation, sprinkler or drip irrigation may be more suitable than surface irrigation because of their flexibility and adaptability to varying irrigation demands on the farm where they are installed. Water application efficiency is higher with sprinkler and drip irrigation than surface irrigation, hence these methods are preferred when water is in short supply. However, it is important to underline that efficiency is just as much a function of the irrigator as the method used. Surface irrigation is preferred if the irrigation water contains much sediment.

The sediments may clog the drip or sprinkler irrigation systems. If the irrigation water contains dissolved salts, drip irrigation is particularly suitable, as less water is applied to the soil than with surface methods. Sprinkler systems are more efficient that surface irrigation methods in leaching out salts.

Surface irrigation can be used for all types of crops. Sprinkler and drip irrigation, because of their high capital investment per hectare, are mostly used for high value cash crops, as vegetables and fruit trees. Drip irrigation is suited to irrigating individual plants or trees or row crops such as vegetables and sugarcane. The main disadvantage of the drip system is that it is usually permanent. Every emitter is dedicated to one single plant, or the configuration could provide more than one emitter to one single plant, as it happens for trees.

Moreover, the type of technology affects the choice of irrigation method. In general, drip and sprinkler irrigation are technically more complicated methods. The purchase of equipment requires high capital investment per hectare. To maintain the equipment a high level of 'know-how' has to be available.

During the analysis phase, it is important to fully understand the environment in which the irrigation system would take place, because water availability would strongly affect the choice of irrigation technique. Not only the climate and rainfall, nor the surface and groundwater resources, but also the distance of water source to fields to be irrigated plays a key role in successful implementation. Introduction of irrigation is a complex process, many factors could determine failure, either technical, agricultural, social or economic. In order to predict as well as possible if the irrigation techniques would be successfully introduced it is essential to evaluate the entire water supply system, farmers should have access to adequate assistance for extraordinary maintenance or to spare parts for system components. If it is introduced a more efficient field irrigation technique with, for instance, a low-pressure pipe distribution system, the network has to be appropriately designed in order to avoid water losses, waste of energy and consequently poor performances. Moreover, in developing countries soil moisture sensor are not widely used in irrigation. Providing the crop with irrigation at the appropriate time and with the correct amount of water still relies on farmer's experience. This is the reason why a particular emphasis has to be addressed to people's awareness of the possible advantages and their acceptance to newer technologies.

Once chosen the irrigation method, the gross water requirement could be evaluated, knowing the efficiency of the irrigation applied. Finally, the distribution network should be designed in order to ensure the adequate pressure levels required by the method. For instance, in low-pressure pipe irrigation, the outlet points should at least guarantee a value higher than the atmospheric pressure, but in sprinkler irrigation, pressures is usually greater, depending on the range the nozzles reach. Knowing the flowrate to be distributed from gross water requirement of the irrigation system in analysis, the design of the network has the purpose to calculate the head losses the water has to overcome. In the case study a simulation program, EPANET 2.0, was used, but the calculation could be completed through an Excel work sheet. A simulation tool simplifies the optimisation of the network and can be used to simulate various working conditions. The results would be the same: the power request for the irrigation system elaborated.

- *Load curve calculation, energy sources and possible exploitation technologies*

All the parameters needed to evaluate the real energy load curve are available at this level of the integrated design. By the calculation of the monthly net water needs of agricultural products in the farm analysed, the gross water needs through the choice of the irrigation that can fit the best these needs and the optimisation of the water distribution network, the energy load curve is determined in terms of energy demand per month. Considering the affecting site dependent parameters, like presence of groundwater or surface water, use of water tanks, rain-fed sectors of land, the daily curve could be estimated.

Then, for the configuration of the energy system, a careful resources assessment is essential, in order to evaluate all the possible configurations of the components and to find the optimum solution.

Along the integrated approach, while studying the way to irrigate and the local constraints, the availability of each energy resource is the main information to be collected. Renewable energies play a great role in this design approach because in many rural areas, the national grid is too far from the installation region, or, when it is accessible, it is not reliable enough to meet local needs.

Through simulation software tools, such as HOMER Pro, Hybrid2, HOGA, it is possible to virtually run different off grid energy plants, both hybrid and renewable.
The computer program used in the case study is HOMER Pro by HOMER Energy, which allows the simulation of all the possible configurations depending on the inputs inserted and the constraints imposed. The simulation proceeds making energy balances for an entire year, choosing only the feasible plants and estimating the cost of installing and operating the system over its lifetime. Then, the optimization phase makes a list of the configurations sorting them by net present cost. The last tool of the software is the sensitivity analysis that repeats the optimization process for each sensitivity variable defined by the user.
There are many energy simulation programs; the one effectively used is not the central issue. What is important is the possibility to simulate a power production plant over a certain period and to evaluate which source fits the best the local energy needs. Particular attention has to be payed to exploitation technologies and their availability in the country of interest. The factors affecting the final choice are copiously described in paragraph 2.4 and they always are site dependent.
At the end of these four steps, the energy-irrigation system is designed considering the deep linkages in water and energy use in food production.

The most innovative characteristic of the integrated approach in the energy system design presented in this thesis is that the calculation of water needs and energy needs happens simultaneously. The simulations of all the possible combinations of crop patterns, irrigation techniques, and energy systems lead to have an overall vision both of real constraints and of real perspectives. The case study is a proof of the strong disconnection could exist between real needs and expected needs of a farm in a rural area where traditional techniques are strongly rooted.

Chapter 6 FUTURE DEVELOPMENTS

The work presented in this thesis could be further developed in those aspects that are not examined in depth. In the case study, data missing still remains a big constraint for the assessment phase, because accuracy in data would mean proper choices about decisive parameters. The main information not available during the collection of data in the Ferrando Ezechiele farm was the water disposal of the three wells, their available flow that could be extracted in a sustainable way along the year. In order to know this information, the water level of the wells should be monitored for at least one year, and a complete pump test should be done to calculate their recovery time, such as the time they need to refill water until their original level. Knowing these values would permit to obtain a precise land surface that could be efficiently cultivated under irrigation through the real water endowment of the farm. Cultivating more land would affect in a negative way all the crops because water would not be sufficient for their correct growth. Moreover, water excessive extraction would jeopardise the resource with consequences for all the farmers of the community. The river from which water is extracted, indeed, is used by several farms, both before and after the Ferrando Ezechiele farm.

The possible problem of climatic data missing, on the contrary, could be partially solved through a detailed database available thanks to Mr Robert D. Van Buskirk, who was senior research scientist in the University of Asmara until late '90. He collected data about rainfall, temperatures, humidity, wind speed for ten locations in Eritrea, along an average of 20 years. The database could be used together with more recent data, to create historical statistics and to calculate different rainfall patterns, for instance a "statistical dry year" or "statistical wet year". To calculate these values, the rainfall totals for a given period should be tabulated, then they should be arranged in descending order of magnitude. By the calculation of the probability to observe the rainfall values listed, it is possible to define as the dry year, the one that has a yearly rainfall value statistically exceeded in 80% of the cases. At the same way, the wet year is the year that has rainfalls statistically exceeded in 20% of the years analysed [27]. Moreover, the database CLIMWAT 2.0 by FAO [69] collects data for the main stations of the country, both sources could be used to find data as reliable as possible. If data accuracy is a prerequisite of the project and there are no tight timeframe, a simple kit to assess solar resource and wind speed is commercially available. If the measurements take place for a sufficient period, results could be used to assess both evapotransiration properties and local energy sources.

The other important missing information was about revenues. In the case study, revenues could be generated by fuel savings and increased agricultural production, in terms of quality and quantity. Nevertheless, the selling activity could not be evaluated because farmers were not able to give reliable information. An excel file was prepared to manage production and selling activities with the aim to build a data baseline which could be compared to newer data, once the energy and water distribution systems would be renewed. The information about current selling activities would be used to calculate yearly cash flow together with the available estimation of yearly fuel saving, and consequently the payback time of the complete investment in energy and irrigation system would be calculated. This consideration is important because in a fragile economy like the one of the case study, an economic analysis could have a high inside risk, typically due to inflation rate. Knowing the payback time of the investment could be an incentive for the farmers to wait until first revenues will be obtained and not to underestimate maintenance. The awareness of farmers about the advantages that the integrated new solution could bring would be strengthen by a complete economic analysis.

The increase in revenue would be a reliable indicator of the enhancement reached through the project. If better water management and sustainable energy exploitation would lead to significantly higher revenues, the integrated approach application would be successful. In order to take into account the increased productivity of the farm, a proxy indicator could be used, for instance the Leaf Area Index (LAI) [71]. The proxy could be correlated to yearly average biomass yield, expressed in $\left[\frac{tons}{ha}\right]$ and the revenue could be obtained through the average market price.

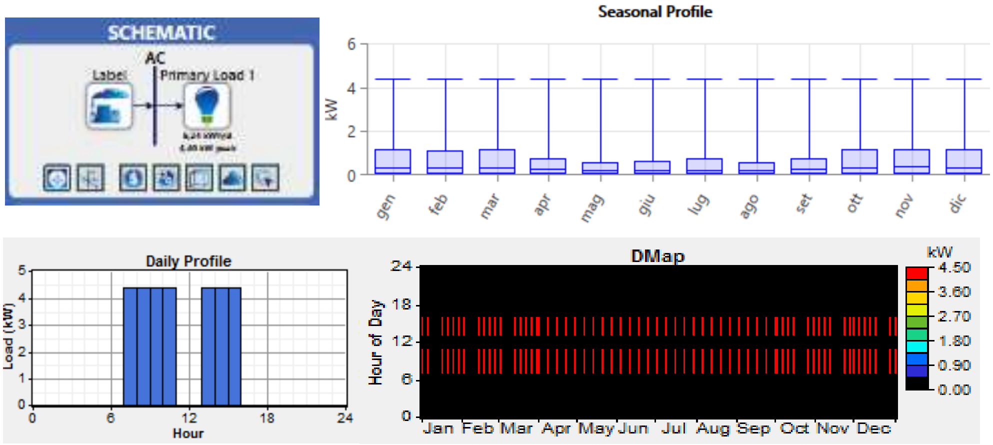
From a technological point of view, the project of the thesis is very feasible; it uses tested technologies largely available on international market. Eritrea suffers heavy penalties in international trade, but it still collaborates with few countries, like China, Canada, South Korea for exports and Egypt, Germany, Italy, Saudi Arabia for imports [72]. For a future development of the integrated energy and water project, it is reasonable to assume that latest technologies could be available in Eritrea. In general, the approach to the energy and irrigation system design could use newer sensors to monitor soil water content and to give instantly feedback. The information on crop water requirements and soil humidity would be more complete and time between the moment when condition changes and the system is aligned on real needs would be much faster. Using these sensors could lead to a complete automation of the irrigation action. If the sensors transmit the information to pumps, they would know when to irrigate and how much water should be distributed, minimising the human involvement regarding the decisions about irrigation scheduling. The energy required to run this advanced system could be derived by a bigger energy system or otherwise by the excess electricity produced when not required.

The project could be enlarged to the community that share the same water resources, the Mai Ainis river, to obtain greater enhancement of local resources management. From a financial point of view, considering a small scale irrigation system coupled with the energy system would be more attractive than a single-farm intervention. Two areas of enhancement are involved: the irrigation efficiency improvement (farmers' interest), with the concerned environmental protection (governments' and NGOs' interest), and the access to energy in rural areas –where both stakeholders have high interest. The clean energy availability derived by the project could be a potential driver to attract funding and considering the theoretical low investment for a single farm, a micro credit business model could be accessible.

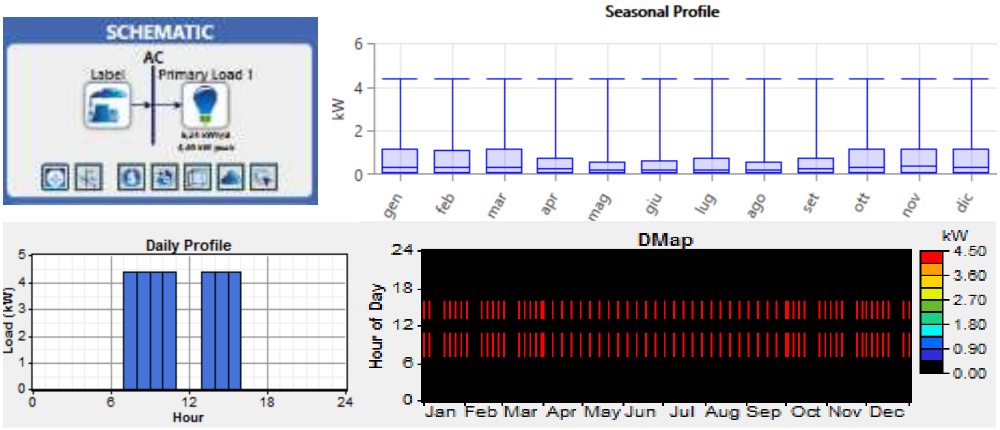
Appendix A Load input

Current situation - Load curve

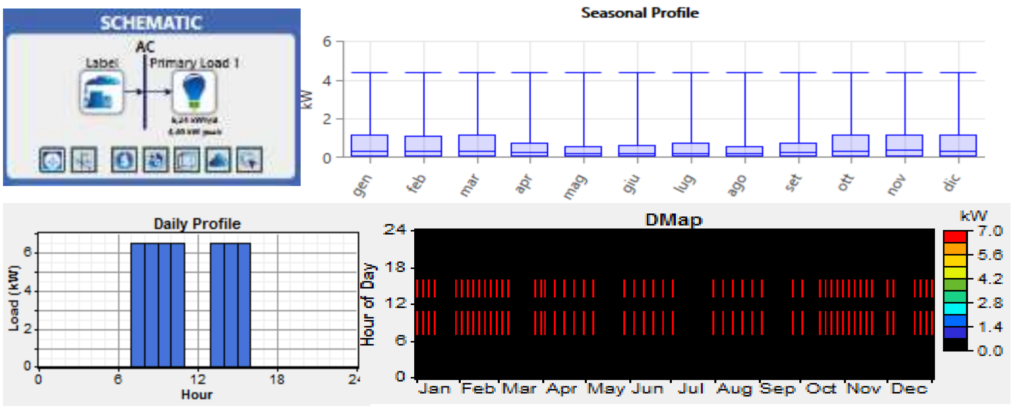
Zone 1



Zone 2

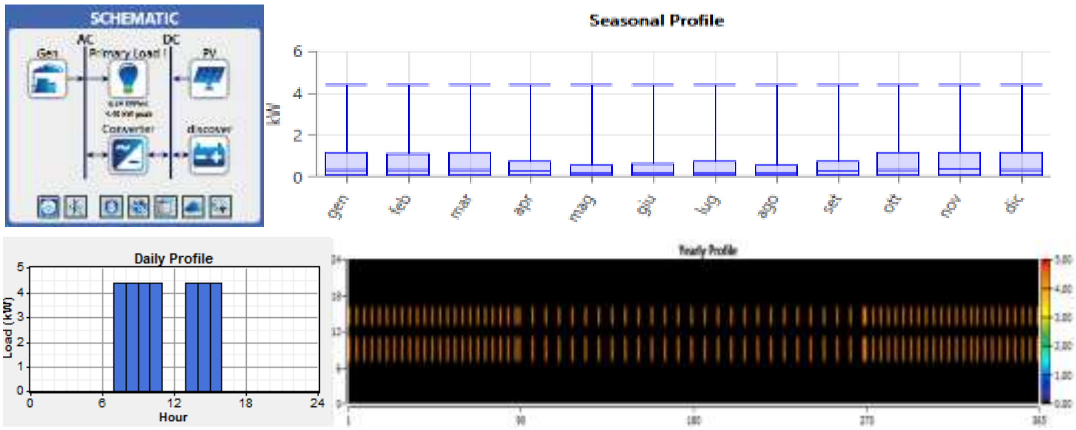


Zone 3

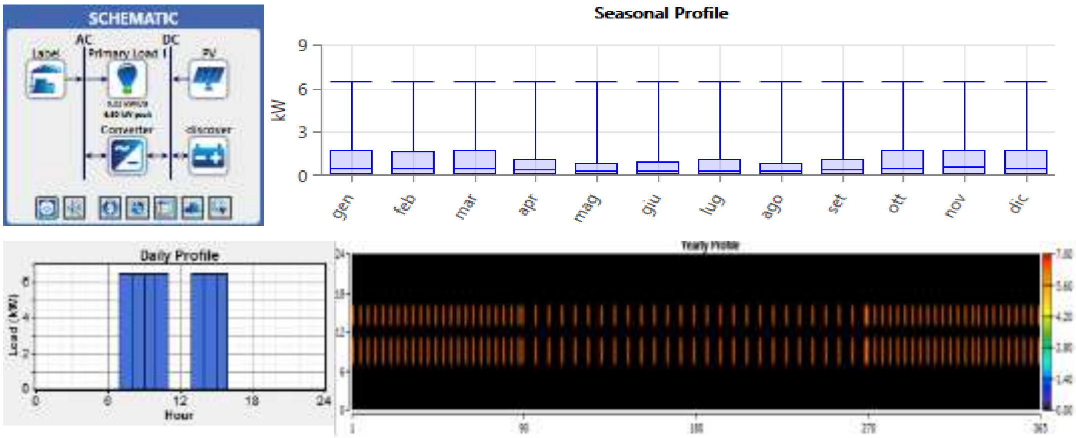


Demand-driven energy system design – Load curve

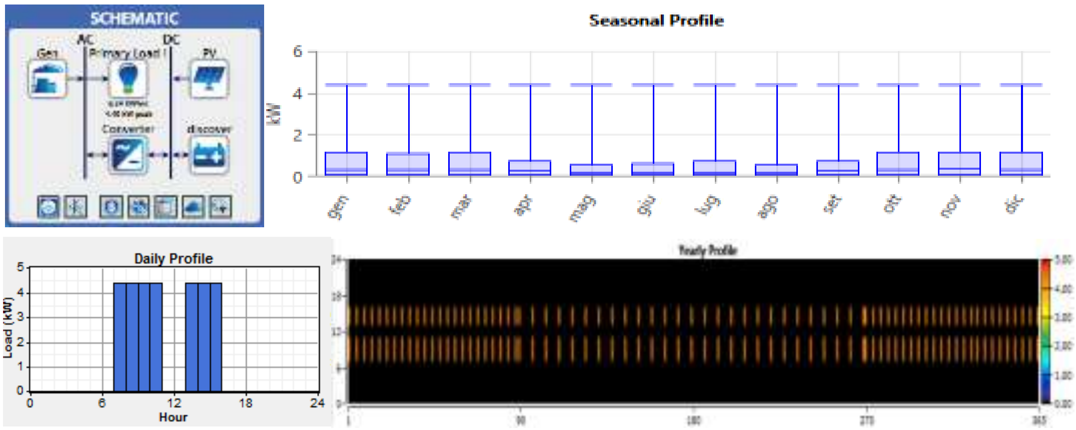
Zone 1



Zone2



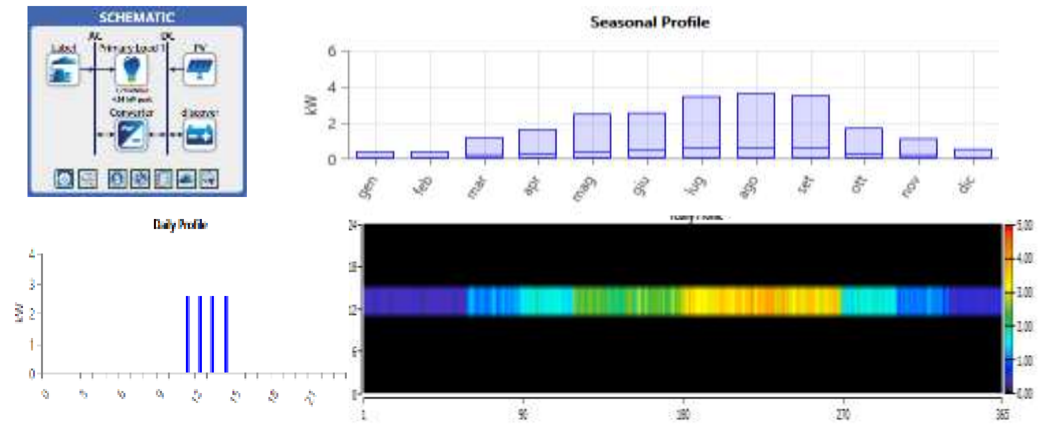
Zone 3



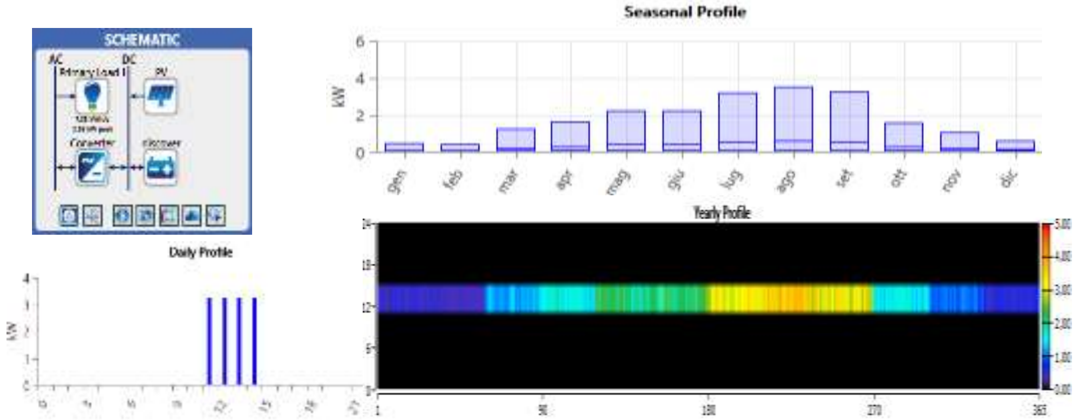
Integrated water energy design - Load curve

CONFIGURATION A

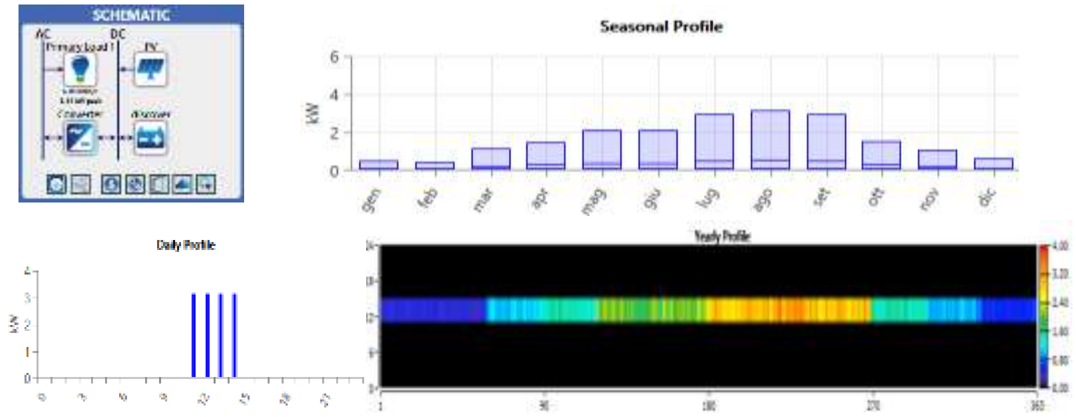
Cumulative traditional irrigation



Cumulative low-pressure pipe irrigation

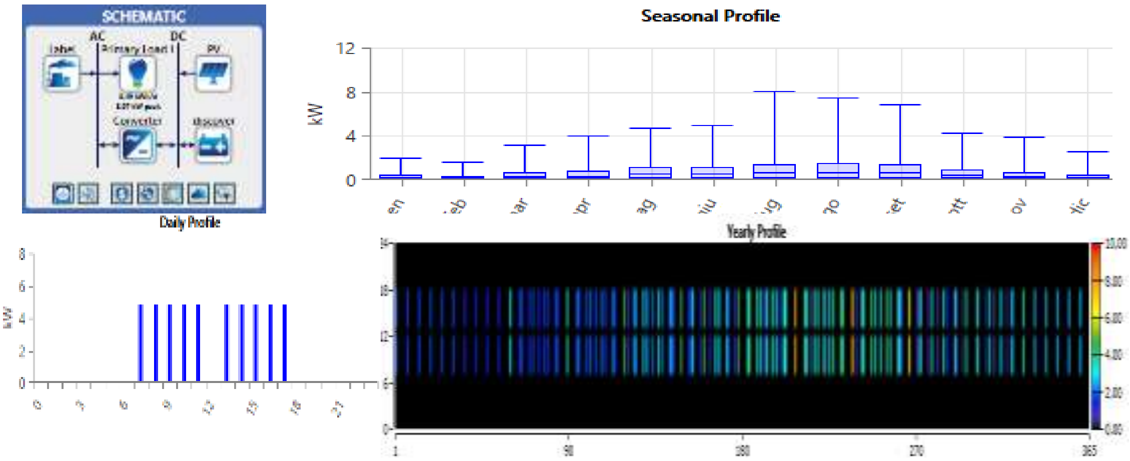


Cumulative sprinkler irrigation

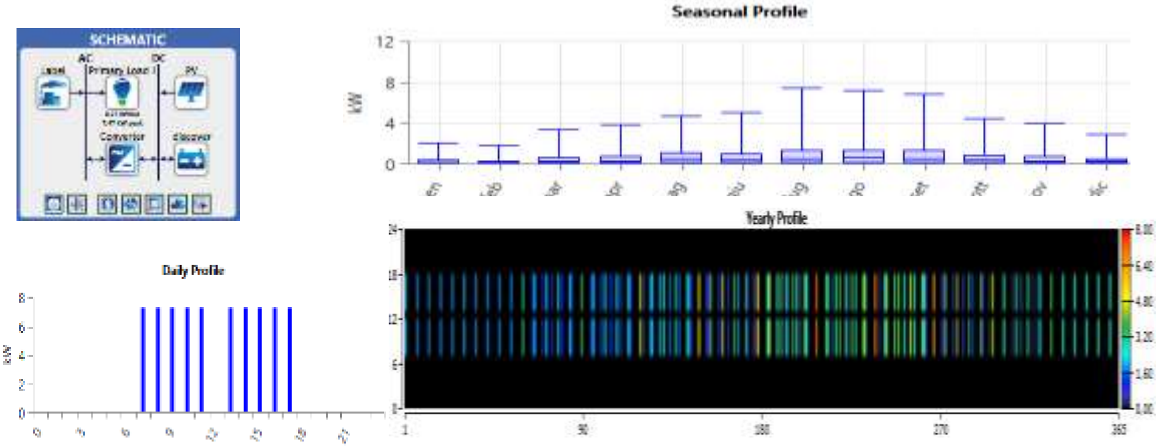


CONFIGURATION B LOADS INPUTS

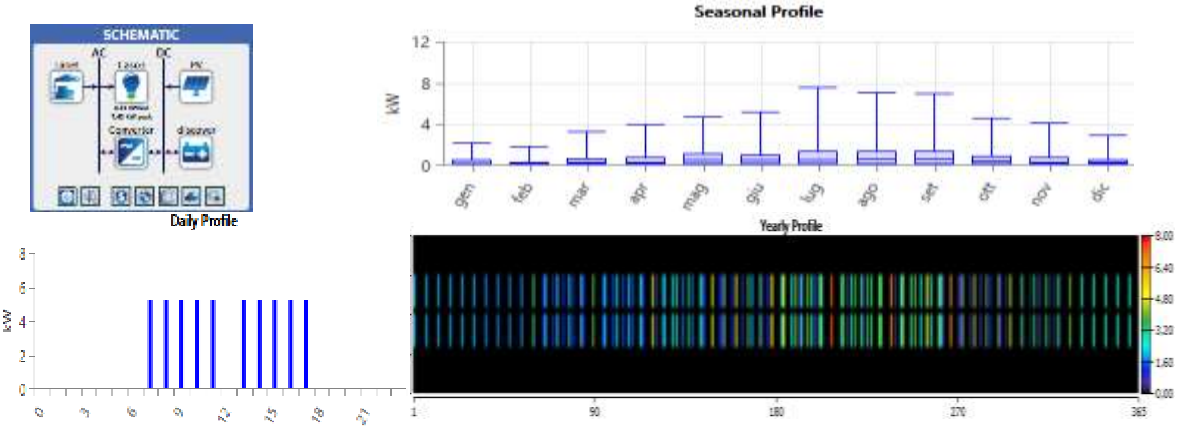
Cumulative traditional irrigation



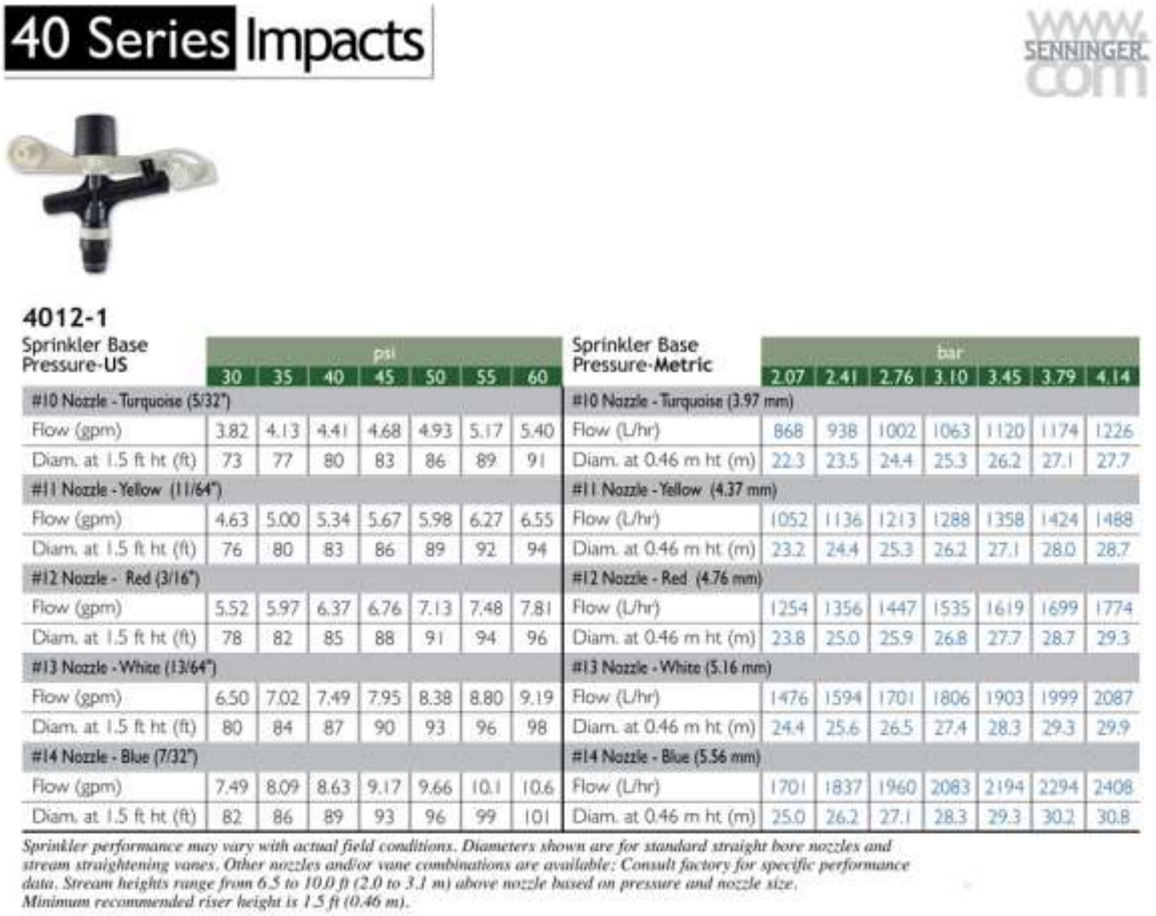
Cumulated low-pressure pipe irrigation



Cumulative sprinkler irrigation



Appendix B Sprinkler data [73]



40 Series Impacts

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4012-1

Sprinkler Base Pressure-US	psi						
	30	35	40	45	50	55	60
#10 Nozzle - Turquoise (5/32")							
Flow (gpm)	3.82	4.13	4.41	4.68	4.93	5.17	5.40
Diam. at 1.5 ft ht (ft)	73	77	80	83	86	89	91
#11 Nozzle - Yellow (11/64")							
Flow (gpm)	4.63	5.00	5.34	5.67	5.98	6.27	6.55
Diam. at 1.5 ft ht (ft)	76	80	83	86	89	92	94
#12 Nozzle - Red (3/16")							
Flow (gpm)	5.52	5.97	6.37	6.76	7.13	7.48	7.81
Diam. at 1.5 ft ht (ft)	78	82	85	88	91	94	96
#13 Nozzle - White (13/64")							
Flow (gpm)	6.50	7.02	7.49	7.95	8.38	8.80	9.19
Diam. at 1.5 ft ht (ft)	80	84	87	90	93	96	98
#14 Nozzle - Blue (7/32")							
Flow (gpm)	7.49	8.09	8.63	9.17	9.66	10.1	10.6
Diam. at 1.5 ft ht (ft)	82	86	89	93	96	99	101

Sprinkler Base Pressure-Metric	bar						
	2.07	2.41	2.76	3.10	3.45	3.79	4.14
#10 Nozzle - Turquoise (3.97 mm)							
Flow (L/hr)	868	938	1002	1063	1120	1174	1226
Diam. at 0.46 m ht (m)	22.3	23.5	24.4	25.3	26.2	27.1	27.7
#11 Nozzle - Yellow (4.37 mm)							
Flow (L/hr)	1052	1136	1213	1288	1358	1424	1488
Diam. at 0.46 m ht (m)	23.2	24.4	25.3	26.2	27.1	28.0	28.7
#12 Nozzle - Red (4.76 mm)							
Flow (L/hr)	1254	1356	1447	1535	1619	1699	1774
Diam. at 0.46 m ht (m)	23.8	25.0	25.9	26.8	27.7	28.7	29.3
#13 Nozzle - White (5.16 mm)							
Flow (L/hr)	1476	1594	1701	1806	1903	1999	2087
Diam. at 0.46 m ht (m)	24.4	25.6	26.5	27.4	28.3	29.3	29.9
#14 Nozzle - Blue (5.56 mm)							
Flow (L/hr)	1701	1837	1960	2083	2194	2294	2408
Diam. at 0.46 m ht (m)	25.0	26.2	27.1	28.3	29.3	30.2	30.8

Sprinkler performance may vary with actual field conditions. Diameters shown are for standard straight bore nozzles and stream straightening vanes. Other nozzles and/or vane combinations are available: Consult factory for specific performance data. Stream heights range from 6.5 to 10.0 ft (2.0 to 3.1 m) above nozzle based on pressure and nozzle size. Minimum recommended riser height is 1.5 ft (0.46 m).

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