A NEXUS APPROACH TO SOLAR PUMPING IRRIGATION SYSTEMS IN NORTH AFRICA: OPPORTUNITIES AND CHALLENGES

A case study of Egypt

MASTER THESIS

Master of Environmental and Energy Management
Faculty of Behavioural, Management and Social Sciences
University of Twente
Academic Year 2021/2022

Olayemi Deborah Popoola | S2717581

Supervisor: Steven McGreevy

Co-supervisor: Kris Lulofs

August 2022

ABSTRACT

Agriculture is a major source of livelihood in semi-arid North Africa and is shifting toward becoming climate-smart by the introduction of solar-powered water pump irrigation systems and promotion of renewable energy for general use. These technologies are being promoted by the government, with funding from organizations to help farmers with the transition from diesel-powered pumping to solar pumping for irrigation. On the other hand, the adoption of this technology might be a threat to the sustainable use of groundwater, such that more policies are needed to minimize the possibility of groundwater depletion.

Egypt is particularly vulnerable to water insecurity. Egypt has limited arable land (96% is desert), low rainfall, water from river Nile for use in agriculture is decreasing, and a substantial amount of its groundwater is over exploited. In terms of energy, energy subsidies are being removed from fossil fuels and SPIS projects are being promoted in off-grid areas and desert regions as solar potential is high. In this region, land reclamation (desert converted to agricultural land) is achieved by irrigation and agriculture is linked to about 85% of total water withdrawal. Therefore, there is a need to manage groundwater withdrawals, especially, with the use of solar pumps as it is considered to utilize “free energy” with low maintenance and operating costs.

The water-energy-food (WEF) nexus approach is used in this study as a framework to assess the benefits and trade-offs associated with the adoption of solar pump irrigation systems (SPIS) in Egypt. The study was carried out to answer the question: What are the opportunities and challenges involved in the adoption of solar pump irrigation system (SPIS), the effects on water and food security, and what governance strategies can be proposed to mitigate the rate of water withdrawals

Data were collected through structured literature review, desk study, and interviews with experts and SPIS projects. The data was used to conceive policy strategies and predict future scenarios through a system modelling tool (fuzzy cognitive mapping using the mental modeler software). Positive and negative scenarios were developed by simulating combinations of policy options in the modeler. The key outcomes of the positive scenarios show a 46% decrease in groundwater withdrawals, 42% increase in farmer’s income, 60% increase in water efficiency, 23% increase food security, 17% decrease in greenhouse gases (GHG) 15% increase in the end-of-life water pollution.

The key findings from this study shows that solar pump irrigation system is indeed beneficial for farmers, as it promotes climate-smart agriculture and can improve their income. With the implementation of better policies, use of policy instruments (well permits, energy tariffs, drip irrigation), the use of smart meters and collaboration between relevant stakeholders during the design of solar projects, over exploitation of groundwater can potentially be controlled. In addition, the primary findings of the system-represented projection show that, without the presence of well implemented policies, the continuous adoption of solar energy for irrigation in sun-rich and renewable groundwater-scarce Egypt is projected to negatively impact groundwater supplies.

Keywords: Solar pump irrigation systems, North Africa, climate change, groundwater governance, food security, solar potential, solar projects, WEF nexus, fuzzy cognitive mapping

ACKNOWLEDGEMENT

First and foremost, I want to express my deepest gratitude to my superiors. My thesis supervisor, Dr. Steven McGreevy, for his unending patience, support, advice, feedback, encouragement, and fantastic discussions during the course of this study. His availability was invaluable and his trust in me boosted my confidence to complete this research. I'd also like to express gratitude to Dr. Kris Lulofs, my second supervisor, for his insightful feedback and helpful suggestions.

Special gratitude to all the interviewees for their invaluable time and responses. Their thoughts and insightful conversations contribute greatly to my thesis and expanded my knowledge.

Finally, I'd like to express my family and friends, whose constant support and words of encouragement motivated me greatly throughout this process.

TABLE OF CONTENTS

ACRONYMS LIST

SPIS	Solar Pump Irrigation Systems
PV	Photovoltaic
MENA	Middle East and North Africa
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GERD	Grand Ethiopian Renaissance Dam
IWRM	Integrated Water Resources Management
WEF	Water-food-energy
USD	United States Dollars
UNDP	United Nations Development Programme
IFC	International Finance Corporation
BCM	Billion Cubic Metres
EWP	Egyptians water policy
WUAs	Water Users Association
SADS	Sustainable Agricultural Development Strategy
CSA	Climate-Smart Agriculture
NDC	National Determined Contributions

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

1.1. Overview

North Africa is a semi-arid region and very vulnerable to the impacts of climate due to its economic dependence on rain-fed agriculture and high incidence of drought (Schilling et al., 2020). North Africa includes the countries of Algeria, Morocco, Egypt, Tunisia, Libya, Sudan and Western Sahara (UNSD, 2022). More generally, a high percentage of Africa's gross domestic product (GDP) depends on agriculture, making it a crucial sector for the continent (Dube et al., 2016; Taylor, 2015). Agriculture accounts for about one-fifth to one-third of Sudan's gross domestic product (GDP) (FAO, 2021), 11.3 percent of Egypt's GDP (USAID, 2022) and 15 percent of Morocco's GDP (ITA, 2020; USAID, 2016). Also, the poor and vulnerable communities in Africa predominantly depend solely on agriculture as a livelihood (Dube et al., 2016).

Agriculture is recognized as one of the major contributors to the severity of climate change related impacts because of land use changes, such as deforestation and irrigation activities (Gupta, 2019). It contributes to 26.1% of the total greenhouse gas emission in Sudan (USAID, 2017), 10% in Egypt (USAID, 2015), and 24% in Morocco (WRI CAIT, 2014). Agriculture can either be rain-fed or through irrigation. More than 80% of the world's water withdrawal is consumed by irrigation, including groundwater withdrawal (FAO, 2016). In the Middle East and North Africa (MENA) region, agriculture accounts for more than 80% of water use, which is higher than the global average of 70% (UNICEF, 2020). Agriculture in North Africa depends on both rainfall and irrigation, and the region consists of the world's second largest irrigated areas, after Asia, with about 43 million hectares of irrigation potential (FAO, 2011; Ringler et al., 2020). Although, North Africa has historically had extensive use of surface irrigation for agriculture, the irrigation system is presently supported and sustained by groundwater resources (Massuel et al., 2017).

Apart from its input to increasing food production and food security, irrigation has lessened the reliance of North Africa on food importation (Ringler et al., 2020). However, due to growing population, persistent conflicts, rapid increase in agricultural demand, governance challenges, poor water management, deteriorating water infrastructures and the extension of irrigated area using non-renewable deep aquifers, such the Nubian Sandstone Aquifer (UNICEF, 2020), North Africa's water supplies for irrigation expansion are nearly depleted, as the region suffers from "hydrological water scarcity" (Ringler et al., 2020). Furthermore, "the region's withdrawals for irrigation exceed renewable resources due to groundwater overdraft and recycling" (FAO, 2011, p.42).

Without the aid of adequate and effective policies and guidelines, ground and surface water withdrawals will continue at higher rate. The use of solar pumps for irrigation, especially in arid regions, has been seen as a promising solution to improve agriculture during drought and reduce GHG emissions from diesel generators (Chandel et al., 2015). Since the operating and maintenance costs of solar-powered pumps are minimal compared to diesel pumps, water withdrawals can be more frequent and sustained longer, which could further lead to groundwater exhaustion and land subsidence in arid regions, hence affecting future food security (Aeschbach-Hertig & Gleeson, 2012). In addition, not much research has captured the impacts of solar pumping irrigation in North Africa region.

1.2. Scope of the Study

This study broadly examined North Africa, reviewing the cases of Egypt, Sudan, and Morocco because these countries are considered as medium and high baseline water stress regions according to the World Resources Institute, the country is considered as high baseline water stress region (Hofste et al., 2019). Also, the governments of these countries have been promoting the adoption of SPIS to achieve emissions mitigation, while securing water resources for agriculture.

Moreover, this study ultimately focused on the cases of Egypt in-depth. Egypt was selected because apart from the Nile valley, 96% of its total land area is covered by desert. Also, there is more pressure on the groundwater resources due to the reduced allocated share of the river Nile (caused by the Grand Ethiopian Renaissance Dam).

This study considered groundwater-related projects executed by government agencies and those supported by international organizations. Such projects have implementation durations of no less than four years and are expected to influence the livelihood of farmers as well as reduce environmental emissions. By implication, food security and water resources are affected.

1.3 Research Objectives

This research analyzed the effects of solar pumping irrigation on water security and food security in arid regions, using the WEF Nexus approach, to suggest possible pathways for adequate policy making and ways to implement the technology more sustainably.

1.4. Research Questions

Main question

What are the opportunities and challenges involved in the adoption of solar pump irrigation system (SPIS), the effects on water and food security, and what governance strategies can be proposed to mitigate the rate of water withdrawals?

Sub-questions

- What are the water resources available and the environmental regulatory in place, and how do they influence the adoption of SPIS?
- What are the effects of solar pumping on water, food and energy resources?
- How can the in-field context be represented in a systematic way to model policy scenarios?
- How might SPIS be successfully adopted without overexploitation?
- What governance strategies can be proposed to temper the rate of agricultural water withdrawals using SPIS?

This section majorly outlined the background and justification of the study, as well as research questions that streamlined and directed the key findings of the research towards governance and water-energy-food (WEF) nexus effects of solar pump irrigation systems (SPIS). The next chapter will presents information about the condition of water resources in correlation with the widespread of solar pump irrigation systems (SPIS) in Egypt, and the North Africa at large.

BACKGROUND

A discussion about the severity of groundwater depletion in North Africa, the factors exacerbating the issues and the repercussions in terms of food security, as well as groundwater governance. Thereafter, a review of the water condition and the rate of adoption of solar pump irrigation systems (SPIS) in North African countries. All these information indicate that SPIS significantly improve the agricultural productivity of this region, however, groundwater resources might take the fall for it.

2.1. Water Security in Semi-Arid Region

According to Cook & Bakker (2012), various policymakers and researchers have given diverse connotations to water security, from discipline-based to multidisciplinary definitions. However, for the purpose of this study, water security involves the access and availability of water in order to achieve long term sustainability (Hoekstra et al., 2018). In addition, water scarcity is generally referred to unavailability of sufficient water quantities for social and environmental purposes (White, 2014). The essential aspects of water security are water demand and water supply and both are important in sustainable development (Wegerich et al., 2015). Therefore, water security management approaches target demand reduction and supply improvement.

In the face of climate change, water resource security in semi-arid and arid regions is most threatened since climate change can also mean less rainfall. Since most semi-arid areas rely on groundwater resources, groundwater recharge is reduced as the maximum temperature increases and yearly precipitation decreases (Emam et al., 2015). Simmers (2003) speculated the significance of considering local hydrological processes in the actions plans for water resources management in semi-arid regions since almost one-third of the earth is categorized as semi-arid or arid.

While several studies and analysis blame climate change for worsening water scarcity in semi-arid areas, socio-economic factors such as income, occupation, and education are also significant in contributing to water scarcity. An analysis carried out by Droogers et al. (2012) indicated that climate change contributes to 22 percent of water shortages in the Middle East and North Africa (MENA) regions while socio-economic factors contribute to the remaining 78 percent. Poor or low-income communities in landlocked countries, where water supply service is the role of the public sector, mostly suffer from water insecurity because of poor road access and tele-communication systems, and expensive groundwater extraction (Raditloaneng, 2012).

Poor water management practices are presently recognized as an important part of the threats to water security, mainly in regions where the climate is getting drier (Bieber et al., 2018). In the climate change adaptation discourse, it is essential to include basin management and water security as the effect on water resources becomes consequential. Also, water management for agricultural productivity will require a re-evaluating, merging solutions for domestic, industrial, and environmental purposes (Falkenmark, 2013). Drier climate countries require strategies and approaches that address the low-hanging fruit, such that, water policy is flexible.

2.1.1. Water Security in Africa

The effects of climate change significantly cripple the social, economic and ecological development of Africa and affects water availability, as the region only contributes 4 percent to total global greenhouse gas emission. Therefore, strategies are required to ensure that specific financial aid is channelled to water insecure regions (GWP, 2022).

Africa is the second most populous continent (World Population Review, 2022), and North Africa is one of the most water-scarce regions in the world (Hofste et al., 2019). The growing population in Africa contributes to the water situation in North Africa where more than half of the population resides in water-scarce regions (Emam et al., 2015; Gude, 2017). This population growth is considered rapid and exacerbated by rural-urban migration as people move to find better economic and livelihood opportunities. An example of migration caused by water insecurity was observed in the case of Angola, a Southern African country which was presumed to have the highest water use efficiency according to the assessment of Africa's water security done by the United Nations (Oluwasanya et al., 2022). Several people migrated from Angola in search of basic needs and economic convenience due to the recent dry period during what was supposed to be the rainy season between 2020-2021 (GWP, 2022).

There are studies which have examined ways to improve the water challenges faced by many vulnerable communities in Africa. A study carried out in the semi-arid regions of Ethiopia highly recommended the use of water saving technologies such as drip irrigation which conveys water precisely to the roots of plants, for semi-arid regions where drought is frequent (Gebru et al., 2021). Water reuse technologies which are cost effective and energy efficient are also suggested as one of the solutions to increasing African water demand (Gu et al., 2017). The use of solar-powered pumps for sustainable access to sufficient water for irrigated farming was also recommended (Lefore et al., 2021; Massuel et al., 2017).

2.2. Groundwater Governance

Groundwater depletion is detrimental to areas that depend on agriculture and groundwater irrigation and this can cause future ecological degradation if not properly monitored (Döll et al., 2014). Moreover, over abstraction of groundwater resulting to global water depletion crisis is also affected by the improved access to affordable water pumping technologies (Wada et al., 2012). Inadequate governance of groundwater can lead to social issues where indigent urban and rural households would be forced to search for alternate water sources, the economic burden of extracting water at deeper depths, and environmental consequences of land subsidence which can damage infrastructure and buildings (Lezzaik et al., 2018). Therefore, policymakers, water users associations and water managers are encouraged to monitor and manage groundwater in order to curb over-reliance on this water source.

In a bid to ensure the accessibility of people to clean and quality water, effective management of groundwater is paramount for areas depending greatly on groundwater for survival. Therefore, in the decision making for management, the interests and perspectives of stakeholders should be considered, especially the inclusion of farmers that access groundwater for drinking and irrigation purposes in the dry season in particular (Bastakoti et al., 2020). A study in a semi-arid region of Iran shows the relation between electricity prices, food security and water security such that a 50 percent increase in electricity cost scenario reduces the benefits from agricultural products by 10 percent and increases groundwater level by 51 percent (Zamani et al., 2022). However, the increase in water price can affect the livelihood of farmers. Therefore, Ghafoori-Kharanagh et al. (2021) points to the need for the participation of actors from water, energy and food sectors to ensure better governance because of their interdependencies. Another option is a policy that offers subsidies for agricultural products as a tool to control ground water withdrawal and at the same time maintain food security (Zamani et al., 2022).

2.3. Food Security in Africa

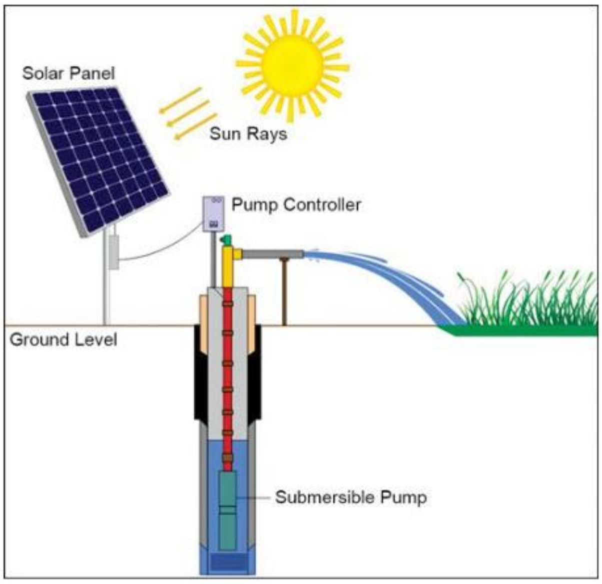
Food security is classified into four aspects by the Food and agriculture organization of the United Nations (FAO): food availability, access, stability, and utilization (WFP et al., 2017). For the past 50 to 100 years, climate change continues to contribute adversely to food security and desertification in Africa since there is increasing water scarcity and poor agricultural yields (UNFCCC, 2020). In addition, the recent Covid-19 pandemic has worsened the economic situation in this region, hence, the number of people affected by hunger continues to increase (Chirisa et al., 2020). According to a report by the Food and Agriculture Organization (FAO) in 2021, more than one-fifth of Africans encountered hunger in 2020 which is higher than the statistics from the previous year (FAO et al., 2021). This indicates that Africa is far from achieving sustainable development goal (SDG) 2 which intends to end hunger. Drought also causes a decrease in soil moisture content, resulting in lower crop yields (Emam et al., 2015).

Issues concerning food security, deteriorated water supplies, rising water demand and decreased land availability in Africa have encouraged the development of numerous novel and sophisticated food production methods using emerging soilless technologies (Obirikorang et al., 2021). The application of soilless culture systems which include hydroponics, aquaponics, aeroponics and supportive mediator's agriculture, saves about 90 percent of water and avails enough land for other crops (Elkazzaz et al., 2017). Hydroponics is a technology which involves the cultivation of vegetables, fruits, herbs and flowers in water without soil, thereby eliminating the complications from soil such as soil-borne diseases (Elkazzaz et al., 2017; Savvas, 2003). Aeroponics system is a sustainable plant growing technique in which plants grow in closed controlled conditions with air or sprayed mist (Elkazzaz et al., 2017; Lakhiar et al., 2018). Aquaponics system is a technology that combines fish production with hydroponics in a closed-loop system such that water and nutrients are recirculated and reuse (Danish et al., 2021; dos Santos, 2018; Elkazzaz et al., 2017).

There is a causal relationship between conflicts and food security (Martin-Shields & Stojetz, 2019). Developing countries such as those in Africa significantly depend on imports for consumption where an increase in international commodity prices can lead to conflicts and grievances against the government but at the same time set a good opportunity for the local producers (Bazzi & Blattman, 2014). In general, reduced labour demand, increased desolation, starvation, migration, or exacerbated social disparities are all examples of how lower agricultural output can directly trigger societal problems (Raleigh & Kniveton, 2012).

2.4. Solar Pump Irrigation systems (SPIS)

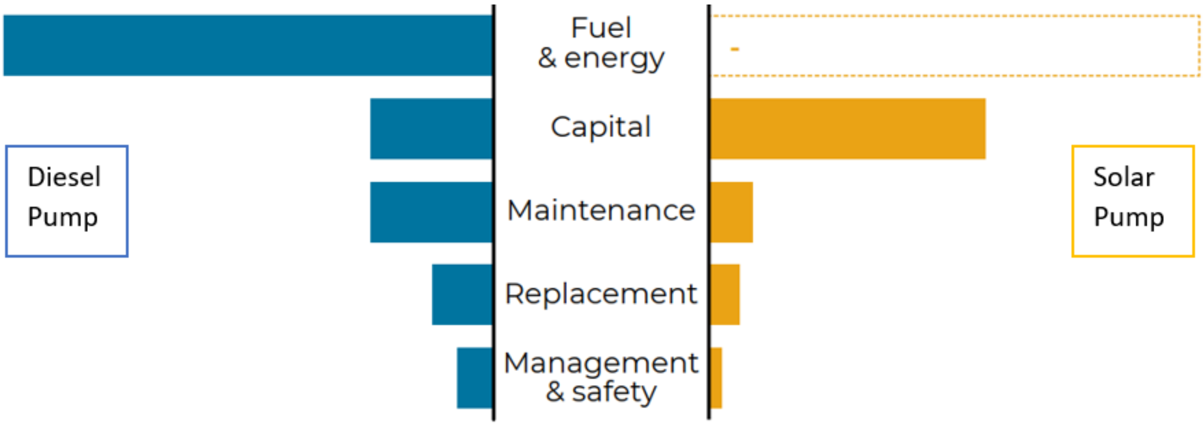
Solar energy is the most abundant renewable source of energy. The application of solar energy for irrigation is widely spreading since it offers access to reliable source of energy and can be used in off-grid areas for smallholder irrigated agriculture or large-scale irrigation (Hartung, 2018). They can provide a very flexible and climate-friendly alternative energy source in rural locations where diesel fuel is expensive or when reliable connection to the electrical grid is limited. Solar pump irrigation systems are also recognised as a climate-smart solution to reduce the carbon footprint of agriculture, since renewable source of energy is utilized (Verma, 2020). Figure 1 shows a simple schematic diagram of a solar water pump for irrigation.



(source: Solar Water Irrigation System -, 2021)

Figure 1. Solar-powered water pump irrigation system (SPIS)

There are multiple factors promoting the adoption of this technology globally. The increasing concerns of greenhouse gas emissions from agricultural activities, the recent hike in diesel prices and the decline in the cost of photovoltaic (PV) panels have encouraged policy makers and government bodies to consider the development of solar energy for irrigation (Bassi, 2015). Another factor is that water pumping using solar energy can be a cost-effective solution to ensure food production and support livelihoods, as solar pumps are less expensive than diesel water lifting technologies (Hartung, 2018). Aside cost, solar pumping system do not contribute to noise pollution compared to diesel pump (Osman Elzubeir, 2016). Figure 2 shows a comparison between diesel pumps and solar pumps in terms of costs. This technology has contributed to increased food production in food-insecure areas such that there is affordable access to water for small farms, thereby contributing to the alleviation of hunger (Lefore et al., 2021).



(source: Salman et al., 2022 p.27)

Figure 2. Comparison between diesel-powered and solar-powered water pump in terms of installation and maintenance costs

Aside from agriculture, solar energy is used for other purposes such as pumping of water for domestic use or for community water supply, lighting purposes, heating purposes, food processing and telecommunication (Sampaio & González, 2017). Solar irrigation technologies are becoming a feasible choice for farmers of different agricultural scale as investment prices for solar powered irrigation systems (SPIS) decrease and incentive schemes for SPIS are implemented (Hartung, 2018). Countries such as Morocco, India, Bangladesh, have been providing subsidies and incentives for solar pump irrigation. Even governments of other North African countries have been providing subsidies and credits for farmers to purchase this technology, coupled with financial aid from international organizations (Brunet et al., 2018; Shah et al., 2018).

On the other hand, there are arguments proposing that solar pumps are not entirely economically viable for farmers, especially in the rural areas. According to (Bassi, 2015), subsidies made the solar pumps economically viable, but only the rich farmers benefits the most in India. Also the article argues that the efficiency of solar irrigation pumps is low compared to diesel pumps because it takes longer for a solar pumps to achieve the same result that a diesel pump of the same horsepower can achieve. More so, many rural areas lack technical know-how for proper maintenance of the solar pumps, hence, affecting the system lifespan (Bassi, 2015). However, a study in Bangladesh shows that solar pumps are profitable for the cultivation of certain high value crops like cotton, strawberry, potatoes etc., compared to diesel pumps (Khan et al., 2014).

In Yemen, an exponential increase in SPIS usage in the last decade and the enthusiasm of farmers to use solar pumps were ascribed to its low cost of maintenance and operation (Aklan & Lackner, 2021). Poor governance and unmonitored water pumping (Aklan & Lackner, 2021) have led to the digging of illegal wells and there is no charge per power unit after construction (Schaer, 2021). Therefore, it is vital to remember that SPIS run the risk of enabling unsustainable water use if they are not properly monitored and regulated.

However, there are cases where groundwater abstraction were properly monitored. For example, a solar pump irrigation scheme in Gujarat, India consists of a Solar Energy Data Management (SEDM) system which collects data from all involved stakeholders, that tracks groundwater impacts of solar irrigation (Power Sector Reform Programme (PSRP), 2021). “Baseline data on crops, existing pumps, and energy use, solar pump usage (hours of use, rate of water pumped and sales from net metering). Remote monitoring system (RMS) devices do not typically display the quantity of water discharged by pumps” (Palit et al., 2021, p.72). The RMS database can be accessed via a GIS program. Although, the impacts are not only ascribed to solar pumps but assess the larger WEF context of the area (Palit et al., 2021).

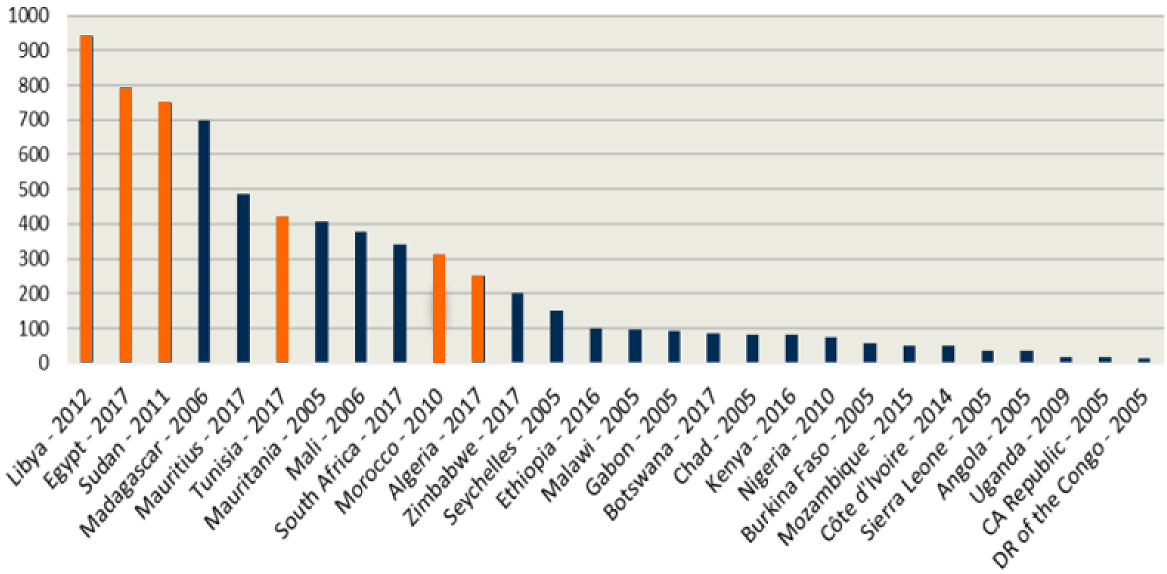
2.5. Water situation and Agriculture in North Africa

North Africa, being one of the most water-stressed regions in the world, is highly dependent on agriculture as source of livelihood and it is also an area combating hunger, varying weather conditions, growing population, increasing transborder conflicts and the effects of climate change on agricultural and rural populations (Baconi, 2018). Therefore, increasing food and agricultural demand are some of the crucial factors worsening the water resources depletion in North Africa (UNICEF, 2020). The circumstances of each North African country are briefly examined, except for that of Egypt, which is more elaborated.

Morocco is a water-scarce, low-income country in Northern Africa with a 710,000-kilometer-long coastline and a typically moderate Mediterranean climate (World Bank, 2018). Agriculture is a key export industry and major economy driver in Morocco, as it accounts for almost 15 percent of the country's GDP and employs 45 percent of the population (ITA, 2020; OECD, 2020). Its useful agricultural area (UAA) is approximately 9,500,000 hectares (95,000 square kilometres) which is 3.11 bigger than the size of Belgium, with about one-seventh being irrigated (Adghough, 2018). It is one of the few Arab countries that has the potential to achieve self-sufficiency in food production. Such that, Morocco initiated a new intensive agriculture policy known as the Green Morocco Plan in 2008 which aims to utilize agriculture as a strategy to alleviate rural poverty, and promote sustainable development and food security (Adghough, 2018; Faysse, 2015).

In 2015, the country experienced 42.7% less rainfall during the planting season due to the El Nino climate pattern, thereby leading to a 70 percent decrease in agricultural output (DTE, 2016). The erratic weather patterns have driven the government to channel investment incentives to help small scale farmers and expand irrigation (Ministerie van Landbouw, 2021). Little progress was achieved since the incidence of drought has increased the dependence of the sector on rainfall in 2019, nevertheless, more investments of over US$500m were allocated to modernize agriculture in 2021 (Ministerie van Landbouw, 2021).

Rainfall potential in Morocco is approximately 130 billion cubic metres (BCM)/year where 108 BCM/year is lost to evapo-transpiration and water resources per capita is predicted to reduce below 500 m^3/capita.year in 2025 (Dahchour & el Hajjaji, 2019). Morocco was one of the first countries to build big dams, with 1.1 million hectares of irrigated land, boosting agricultural production (Adghough, 2018). Thirteen big dams with capacity above 150 mm3 each, have been built for irrigation since the 1960s (Boelee & Laamrani, 2004). Morocco's water usage is comparatively high (Figure 3), with annual water withdrawals of 60% of the country's potential freshwater resources (Diaco et al., 2020). Morocco faces depleting groundwater reserves, as well as a high reliance on rain-fed agriculture, in addition to being water stressed and drought-prone (Bouchaou et al., 2011). Due to groundwater depletion, the Moroccan government encourages the use of drip irrigation since it is cost-effective and water-saving (Kooij, 2016).



(source: Diaco et al., 2020; FAO AQUASTAT, 2022 p.10)

Figure 3. Water withdrawal per capita in North Africa in comparison with other countries (Year indicates time of measurement)

Sudan is located at the connection between the Arab region and Sub-Sahara Africa, and it is bordered by seven countries, (FAO, 2021), and it has a subtropical climate characterized by desert climate in the dry north and tropical rain forests in the south (Basheer, 2008). The economy of Sudan largely relies on agriculture. About 80 percent of Sudan's population depends on agriculture for survival and this sector amounts for about one-fifth to one-third of the country's GDP (FAO et al., 2021).

The reoccurrence of drought and conflict history have negatively impacted the agricultural sector, such that around 12% of the population is predicted to be malnourished in the coming years (FAO, 2021). In a recent report by the Integrated Food Security Phase Classification (IPC), 20% of Sudan's population (especially rural communities) is predicted to face adverse food insecurity in the coming lean periods (between June-September), therefore, the Ministry of Agriculture solicits for accelerated investments in food production from active organizations of the United Nations and the government (IPC, 2021; WFP, 2021). Most rural farms are rain-fed and intensely cultivated. The large mechanized farming practice in Sudan, with water-intensive cotton as the major export crop grown, has led to more spreading of the arid condition of Sudan, particularly due to the kind of irrigation system used which is flood irrigation (Abdalla & Abdel Nour, 2001). In addition, irrigation has been regularly mentioned and identified as a method of advancing food security and economic growth, poverty reduction and climate adaptation in Sudan (Burney et al., 2010; Polak & Yoder, 2006).

Sudan's survival is dependent on its excessive usage of its water resources, where 97% of water consumption is from agriculture (Barton, 2022). About 30% of its agriculture is irrigated by “small traditional spate irrigation and via khors, small mostly hand dug canals, or via huge irrigation projects, such as the Gezira project, which uses about 35 percent of Sudan’s water, and the many giant sugar irrigation schemes” (Sullivan, 2010, p1). Sudan has a great aquifer reserve ranging from the Great Nubian Sandstone to the Umm Ruwaba, as well as the Nile River Basin which supplies about 855 percent of water consumed in Sudan (Basheer, 2008; Sullivan, 2010). The majority of its groundwater reserves, such as the unregulated Nile River Basin, is shared with neighbouring countries like Egypt, and this often cause rivalry (Barton, 2022). However, increasing water demand and desertification became an issue as rural Sudanese frequently flee their homes due to water scarcity and low food production (Barton, 2022).

2.5.1. Solar pump irrigation system (SPIS) in North Africa

Generally in North Africa, renewable energy usage remains significantly underdeveloped in comparison to its potential (IEA, 2020). In 2017, fossil fuels accounted for more than 80% of total energy consumption as seen in Table 1. Sustainable energy usage and access to energy in the agricultural sector has advanced notably in Morocco, particularly with the expansion of electricity between 1992 and 2013 (Malabo Montpellier Panel, 2019). Morocco has great solar energy potential of “an average incident solar radiation ranging from 4.7 to 5.5 kWh/m^2/day, with a number of sunshine hours varying from 2700 hours/year in northern Morocco to over 3500 hours/year in the South” (Mergoul et al., 2018, p.2). As a result, the development of solar power helps to decrease the energy imports of the country and cater for electricity and water demand in rural areas (Abdourraziq et al., 2017).

In Morocco, the utilization of renewable energy, particularly solar energy for water pumping, is crucial for both drinking and agricultural purposes, particularly in light of the country's new energy policy. According to a market survey in Morocco, the market for solar pumping in Morocco has grown significantly in recent years, compared to the usage of wind energy (Mergoul et al., 2018)**.** The country has been making efforts to monitor the use of its water resources by supporting water-saving methods of irrigation and solar pumping, since it was discovered that the prolonged traditional irrigation systems are not water-conserving (Mergoul et al., 2018). The use of solar pumps by farmers has further become more prominent because of the fuel subsidy that was ceased in 2014, and also because it is more cost-effective than the diesel pump (Mergoul et al., 2018). Energy, water and environment government agencies often collaborates to execute solar pump irrigation projects, where solar pumps are installed to replace diesel pumps.

Table 1. Selected water, energy and food indicators in North African countries

	Total renewable water resources per capita 2017 (m^3/inhab/yr)	**Employment in agriculture 2019 (% of total employment)**	**Share of fossil fuels in total primary energy demand 2017 (%)**
Algeria	282	9	100
Egypt	596	21	97
Libya	106	16	99
Morocco	815	33	89
Tunisia	404	14	89
Sudan	926	38	80

Note: A country is recognized as water-scarce if it has less than 1 000 m^3/inhabitant/year
(source: EIA, 2019; FAO AQUASTAT, 2022; IEA, 2021; World Bank, 2021)

Solar potential in Sudan is high, especially in the Northern state which has a desert climate and less cloudy skies (Omer, 2007) and solar energy has generally become the main source of primary energy for rural areas in Sudan (Osman Elzubeir, 2016). The majority of Sudan's climates are conducive to solar pumping which can both be used for clean drinking water and irrigation (Omer, 2001). Most of the agricultural farmlands are far from electricity grid, therefore, rural farmers mostly depended on diesel pumps for irrigation (Osman Elzubeir, 2016).

The adoption of solar pump irrigation in Sudan was initially difficult since it has to compete with the conventional irrigation systems (diesel and electric) because of its high initial cost and solar radiation fluctuations (Ali, 2018; Trainer, 2013). A study in selected places in Sudan shows that solar pumping for irrigation is economically and technically better than diesel pump irrigation system (AbdelGadir & Hammad, 2014), and another study shows that photovoltaic water pumping is the most cost-effective solar irrigation system to use and to promote sustainable development in Sudan's agriculture (Ali, 2018). The government of Sudan has been collaborating with United Nations specialized agencies in projects involving the replacement of diesel-powered pumps with solar-powered pumps (Osman Elzubeir, 2016). Authorities are also encouraging solar-powered drip irrigation, especially during the dry season (Burney et al., 2010).

2.6. Water situation and Agriculture in Egypt

Egypt is an arid country located in the far North-Eastern part of Africa with 96 percent of its land area occupied by desert (Khalifa & Abdelall, 2019). The country's climate varies from semiarid in the north to hyper-arid in the south and it's predicted to go drier as 2050 approaches (USAID, 2018). The Western Desert in Egypt is one of the most arid regions in the world and it occupies about 66 percent of the country's total land area (Khalifa & Abdelall, 2019). Since rainfall is scarce, Egypt has depended largely on the Nile river for centuries (Abd Ellah, 2020) and most of the Egyptian population are located in the Nile Delta, concentrated along the banks of the river (Ibrahim et al., 2018). The Nile river provides 90% of Egypt's overall water demand and 85% of this is used by agriculture (Devaux, 2019; International Crisis Group, 2019). As there are limited water resources because of its stipulated share of the Nile resources, Egypt is among the list of countries that will experience water problems in future due to increased population, limited groundwater and reduced rainfall (Abd Ellah, 2020; International Crisis Group, 2019; USAID, 2018).

Agriculture is a significant part of the Egyptian economy, accounting for 11.3 percent of the country's GDP, as it contributes to food security and exports revenue (Devaux, 2019). Agriculture employs 28 percent of the workforce, while it employs almost 55 percent of the workforce in Upper Egypt (USAID, 2022). Nevertheless, the cultivable land area is just 2.8% of the total land area and it is mostly in the "Nile area" and few "Sinai Peninsula oasis" (USAID, 2018). Agriculture is primarily irrigated and totally reliant on the Nile river's flow, therefore global warming and the reduction in the already scarce rainfall are projected to increase the amount of water required for crop production (USAID, 2018). Since 1978, the United States Agency for International Development (USAID) has been supplying technical support worth about 1.4 billion dollars to rural Egyptian farmers to improve rural agri-business (USAID, 2022).

In Egypt, there are challenges with water resources as concerns arise concerning water availability in the Nile River for agriculture, particularly after the construction of the Grand Ethiopian Renaissance Dam (GERD) (Devaux, 2019). While the constructed dam means less water downstream. The Egyptian government speculated that the dam will effect farmer’s livelihoods (International Crisis Group, 2019), but it is presently difficult to estimate the extent of the impact of Ethiopian’s dam on Egypt’s food production (Devaux, 2019). Groundwater resource in the Nile and desert aquifers are hardly renewable and account for only 12% of Egypt’s water needs (A. M. M. Soliman & Solimsn, 2019). Due to Egypt's excessive groundwater usage, the safe yield has been exceeded, the aquifer systems have been overexploited and some aquifers are under threat by saltwater intrusion (Abd Ellah, 2020).

2.6.1. Solar pump irrigation system (SPIS) in Egypt

As a sunbelt country, Egypt possesses high solar radiation intensity (2600kW/h) and aims to achieve 20 percent of its power consumption as solar-generated according to the national energy goal for 2027 (Abdou & Ibrahim, 2019). Solar-powered pumping is being widely used in Egypt for the supply of drinking water and for irrigation purposes. In Egypt, solar water pumps have enabled people to move from the congested areas to the deserted part of the country where they take advantage of the sun to extract groundwater resources for livelihood and agriculture (Abdou & Ibrahim, 2019). Initially, farmers explored the Western desert using diesel-powered pumps since diesel was subsidized by the government, but now, “self-contained concentrated photovoltaic (PV) systems” steer the whole irrigation system (Abdou & Ibrahim, 2019). As fuel subsidies are reduced due to economic issues, solar pumps have gradually became competitive replacements for diesel pumps (A. Soliman et al., 2017). Residents of off-grid areas also took advantage of solar-powered water pumps since diesel prices increased and it became more difficult to move fuel to where it was needed (Ramsey & Mustard, 2012).

The development of solar-powered pumping systems offers a fantastic opportunity to forego the use of unreliable and unsustainable diesel-powered generators, thereby helping to mitigate the risk of fuel price fluctuations (A. Soliman et al., 2017). As a result, crop losses from inadequate irrigation will never occur. Similar to other North African countries, the initial cost of SPIS is high but on the long run, it is economically viable because $1m^3$ of irrigation water is estimated to be 0.45 L.E. (Egyptian pound) with diesel pump as against 0.28 L.E. of solar pumps (Abdou & Ibrahim, 2019; A. Soliman et al., 2017).

This section reviewed the water resources and adoption of solar pumps in different countries in North Africa, especially Egypt, thereby showing effect of climate change on food security and water resources, and the positive acceptability of solar irrigation system among farmers in semi-arid region. The previous discussion of water and food needs in North Africa requires us to think across multiple governance fields and inter-sectoral discourse in order to make better decisions concerning agricultural water-related technologies. The next chapter will describe the water-energy-food (WEF) nexus framework which serves as a guide to define gathered research data.

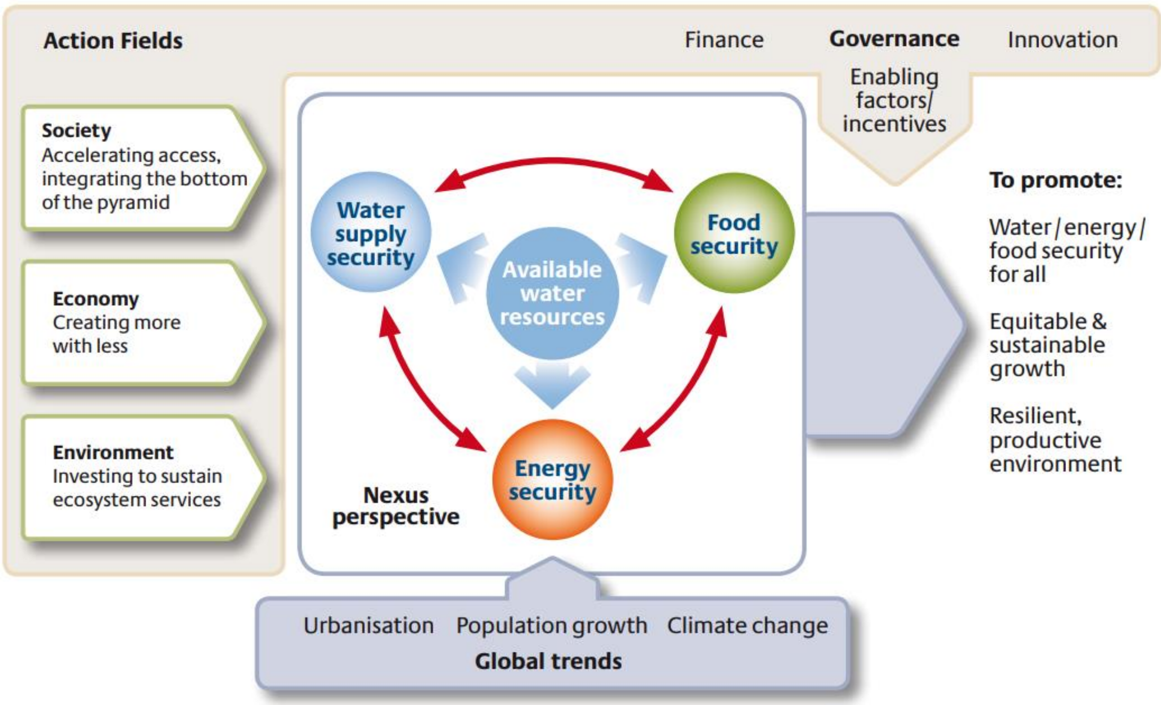
CONCEPTUAL FRAMEWORK

In theory, possible conceptual frameworks for this study include the water-energy-land nexus/framework (El et al., 2016; Johnson et al., 2019), water-energy-environment framework (Asgharnejad et al., 2021), water-energy-food (WEF) nexus (Simpson & Jewitt, 2019), environmental-livelihood-security nexus (Shannak et al., 2018), water-energy-greenhouse gas nexus using life cycle assessment (LCA) (Nair et al., 2014). For this study, I have chosen WEF Nexus, because the framework efficiently matches the scope of the study and include the basic elements of agriculture. Other framework are too broad (wide cross-sector capacity) for this study, with complex methodologies that require further development.

3.1. Water-Energy-Food (WEF) Nexus

This section reviews and identifies the literature on the nexus framework, nexus interlinkages and nexus governance.

The WEF nexus approach minimizes the one-dimensional (silo) decision making process and incorporates the complex interdependencies between sectors as an integrated process. "The WEF nexus is, therefore, the study of the connections between these three resource sectors, together with the synergies, conflicts and trade-offs that arise from how they are managed" (Simpson & Jewitt, 2019). Hoff (2011)presents the new nexus approach that considers the interdependencies of WEF and climate policy; a framing that identifies synergies and trade-offs; and guiding principles that entails the sustainability of ecosystem services, resource efficiency and accessibility (Figure 4). The interlinkages include water for food and food for water, energy for water and water for energy, and food for energy and energy for food (Hoff, 2011). For the purpose of this study, **water for food**, **energy for water** and **energy for food** will be assessed.



(source: Hoff, 2011, p.16)

Figure 4. The Water-Energy-Food Security Nexus.

In the past years, there have been different framings of the nexus and various analytical tools due to the ambiguity of its meaning, as well as various debates concerning the omission of social issues such as inequality, and including only the technical aspects in the framing of the nexus (Allouche et al., 2015). Criticism also emanated because governance, livelihood and environment discourse were not regarded by the nexus (Leese & Meisch, 2015; Simpson & Jewitt, 2019). The conceptualization of the WEF nexus has also been criticized to be water centric since according to WEF (2011), ground water is depleting globally and water has no alternative unlike energy resources. The WEF nexus started to gain recognition in policy and development matters since 2008, and through 2011, there has been readjustment with new additions such as considerations for climate change, land, ecosystem and livelihood. (Allouche et al., 2015; Simpson & Jewitt, 2019). There are also tailored and collaborative frameworks which are developed with the perspective of WEF nexus, such as WEF nexus and sustainable livelihood (of farmers) framework used to evaluate the impacts of hydropower development in a river basin in China (Zhong et al., 2022).

In relation to water governance, the Integrated Water Resources Management (IWRM) approach has been adopted in the Millennium Development Goals (MDGs), however, there have been arguments that condemn the insufficiency of IWRM for sustainable development

(Benson et al., 2015; Bogardi et al., 2012). This is due to the water-centric nature of the framework which doesn't include the expertise of other sector such as food and energy. (Benson et al., 2015)Apart from the WEF nexus approach, another framework for analysing nexus is the Climate, Land, Energy and Water (CLEW) framework which was initially adopted by the International Atomic Energy Agency for biofuel chain analysis (Ramos et al., 2021). Furthermore, with the advent of water-energy-food nexus, the way we think about our natural resources has changed (McGrane et al., 2018).

The concept of Water-Energy-Food nexus is relevant for this study because of the inclusion of food, which is the basis of agricultural production and also, food security is the one of the major reasons for the adoption of solar pump irrigation systems. The world is facing rapid population growth, economic growth and environmental degradation, and North Africa is at the verge of water scarcity and desertification. The framework will help identify the linkages between water resources and food security by considering the adoption of solar-powered pump irrigation system and the projects promoting it. SPIS ensures the pumping of water for irrigation to improve agricultural yields (water for food); involves the extraction of water with the aid of renewable source of energy (energy for water); and promote the expansion of agricultural land using "free" energy from the sun (energy for food). Irrigation is significant in the nexus thinking because improving irrigation means more land productivity, which equally leads to more water requirements that increases energy usage (Rost et al., 2009).

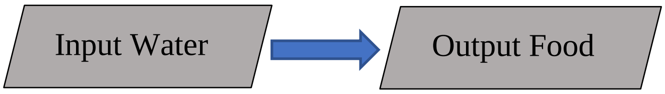
3.2. Interlinkages across the nexus

3.2.1. Water for food production

Agriculture is the largest consumer of water, responsible for about 70% of the global freshwater and Africa and Asia use over 80% of water for agriculture (FAO, 2009). Also, irrigated farmlands accounts for 40% of total food production in developing countries and the percentage is expected to increase up to 50% by 2030 (FAO, 2009). This implies that irrigation activities will relatively increase as much as food demand increases. Therefore, food demand is directly (crop growth) or indirectly (animal rearing) influenced by the presence of in-situ water resources (D'Odorico et al., 2018). The interdependencies between water and food is substantial, therefore, blue water (water extracted from surface or groundwater sources) can determine the increase in crop yields.

Carr et al. (2013) projected agriculture's water footprint to be 11.8 x 10^{12} m^3 per year in 2010 with green water (plant transpiration of rain water) accounting for roughly 78 percent and blue water (surface and groundwater reserve) for 22 percent. Because some of this water is not "evapo-transpired" and can be reused downstream, the global consumption of blue water for irrigation is 0.90–1.28 x 10^{12} m^3 /year which is less than the global water withdrawals for agriculture (2.41–2.56 x 10^{12} m^3 /year) (D'Odorico et al., 2018; D'Odorico & Rulli, 2013). Because the green and blue water involved have different alternative uses and thus opportunity costs, it's vital to distinguish between rainfed and irrigated agriculture since blue and green water serve different purposes and require different energy sources (Hoff, 2011).

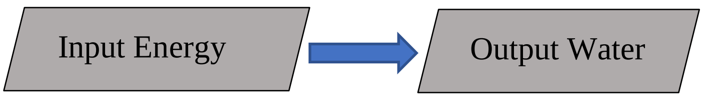
Food's water footprint varies greatly depending on the kind of diet, calorie absorption and how it is allocated among plant and animal sources (D'Odorico et al., 2018). Consequently, water requirement in agriculture can also depend on the type of crop cultivated. Agricultural production could be boosted in drought-prone areas shifting to drought-tolerant crops, lowering water demand and making water available for other uses in the nexus. Micro-irrigation, on the other hand, could cut water usage but may raise total energy usage (Skaggs et al., 2012).



3.2.2. Energy for water

The interlinkages between energy and food can include pumping, moving, distributing and treating water (Hoff, 2011). Energy is required for water supply, and lately, the quantity of energy necessary for irrigation, supply of safe drinking water and wastewater treatment has received more attention (IEA, 2016; Vora et al., 2017). Almost 50% of total irrigation water comes from groundwater (Siebert et al., 2010) and the pumping from this water source is relatively energy intensive compared to surface water bodies, depending on the increasing depth. Alternatively, transporting surface water where gravity cannot work, can require extra energy, for example, the South-to-North water transfer project of China (IEA, 2015).

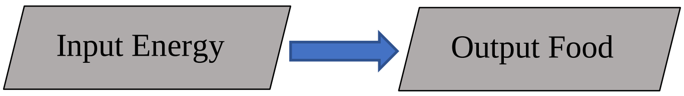
Pumping of groundwater for irrigation requires a large amount of energy supply (WEF, 2011), such that 20% of India's electricity and half of its hydropower generation are used for water pumping for irrigation (Hoff, 2011). According to the FAO (2009), Africa has only used about 5 percent of its renewable energy sources, thus, capacity to greatly improve agricultural irrigation is possible. Therefore, solar energy can be leveraged on since the source is cheap, however, water overdraft can become an issue.



3.2.3. Energy for food

Energy in food production activities has contributed immensely to increasing farm yields through mechanization and other measures that reduce human labour, ranging from "cultivation, processing, packaging, transporting, refrigerating, to the preparing of food" (Ingram, 2011). However, there has been a large increase in energy inputs for irrigation land preparation, etc. (Hoff, 2011). As the fear of the difficulty in meeting future food demand is increasing and lingering, future energy demand for agriculture is bound to increase too. Despite the fact that agriculture's share of total global energy consumption is significantly lower than agriculture's share of total global water usage, intensive agriculture is extremely energy demanding (Hoff, 2011). Consequently, about 30% of total world energy demand is accounted for by the food production and supply system (Hoff, 2011). The close relationship between food and oil prices reflects agriculture's substantial energy need (Kim, 2009), such that agriculture becomes less cost effective with high energy charges.

The interrelation between energy and food can be observed in the electricity subsidies available to farmers for water pumping (Bardi et al., 2013). FAO (2017) highlighted the various means by which food systems can be "energy-smart" which are substitution of energy source with renewables, increasing access to sustainable sources and increasing efficient usage of energy. The adoption of solar-powered pump irrigation system is a promising initiative that could help farmers towards becoming energy-smart, which is a synergy between food and energy sectors.



3.3. System representation and modelling of nexus approaches

The nexus frameworks offer a systems thinking approach that explains the advantages and trade-offs across WEF systems, aids in understanding the complexity and natural boundaries of our environment, and develops successful sustainable development strategies (Liu et al., 2018). However, this frequently increases model complexity, data requirements, and computing effort. The nexus notion must therefore be transformed into understandable frameworks and tools that can be used in decision-making (Vinca et al., 2021). Some of the useful WEF modeling tools include:

Nexus simulation system (NexSym) - NexSym is a software that is being used to examine the sustainability of a local production system for food, energy, water, and other goods and services

(University of Oxford, 2022). In comparison to other tools, it focuses on local/regional scale, providing comprehensive projections for any given design ("in terms of the choice of technological options, scale of operations, and connections between the technological system components and ecosystem components") (University of Oxford, 2022). NexSym was used in the assessment of a UK eco-synergistic town's nexus design by Martinez-Hernandez et al., (2017), "to enhance local nutrient balance and meet 100% of electricity demand, while providing higher carbon capture, biomass provisioning, water reuse, and food production, with a significant impact on land use".

Integrated multisector multiscale modelling (IM3) - Using a combination of open-source process-based human and natural system models, IM3 is able to predict the susceptibility and resilience of the United States (US) from local to global scales to both short- and long-term impacts of natural occurrences and socio-economic factors (PNNL, 2022). Researchers in the United States used computer simulations to investigate the co-evolution between human and natural landscape change in response to both sudden and long term events, by exploring the responses of interconnected energy, water, land, and urban systems to these changes (PNNL, 2022; Voisin et al., 2020).

WEF nexus tool 2.0 - This modeling tool was use to evaluate and quantify domestically produced foods in Qatar (*WEF NEXUS Tool 2.0*, 2014). The inter-relation existing between the water-energy-food systems was established water requirement, energy needs, land requirements and cost of local production (Daher & Mohtar, 2015). The WEF Nexus Tool allows inputs that depict national food, water, and energy strategy alternatives and enables the design and evaluation of various scenarios. Then, "the tool assesses the given scenario by calculating total water requirement for the scenario (cubic metres), total land requirement (hectares), local energy requirement (kilojoules), local carbon footprint (ton CO_2), financial cost (US dollars), energy consumed through import (kilojoules), carbon emission through import (ton CO_2)" (Daher & Mohtar, 2015 p.9).

WEAP ("Water Evaluation And Planning" system) tool - Freshwater management issues are becoming more prevalent, therefore, supply, demand, water quality, and ecological factors must now be fully integrated when allocating limited water resources among "agricultural, municipal, and environmental applications" (SEI, 2021). The software is user-friendly and adopts an integrated strategy (policy scenarios, water balance, stakeholder process) for planning water resources (ranging from surface and groundwater sources to run-off and wastewater treatment) (Momblanch et al., 2019; SEI, 2021).

Global Hydro-economic Model (ECHO) - The ECHO model is a “bottom-up system analysis tool” used to create comprehensive, long-term plans for the water infrastructure (IIASA, 2021). It can help us prepare for the effects of evolving socioeconomic and climatic conditions on the water system and make policy decisions that are both efficient and long-term (IIASA, 2021). Kahil et al. (2018) suggested ECHO as a suitable instrument for analyzing potential water-related scenarios and assessing alternative management strategies.

COFFEE (Computable Framework For Energy and the Environment model) - The COFFEE models were created in Brazil, and are used to evaluate the efficacy of various climate, land, energy, and environmental policies by informing experts and policymakers about the range of feasible approaches to future development and the consequences of various climate change scenarios (IAMC, 2020). The model provides long-term (up to 2100) evaluations of the relationship between the economy, energy and land-use systems (IAMC, 2020; Rochedo, 2016).

Integrated Model to Assess the Global Environment (IMAGE 3.2) – IMAGE was first created in the 1980s which concentrated primarily on climate change, however the recent version was developed in 2020 focusing on environmental challenges and sustainability (Netherlands Environmental Assessment Agency, 2021). IMAGE models the impacts of human activities on global environmental and portrays the interactions between society, the ecosystem, and the climate system to analyze climate change, biodiversity, and human well-being (Netherlands Environmental Assessment Agency, 2021). IMAGE explores the long-term dynamics and repercussions of global changes caused by socio-economic and environmental causes, by building environmental assessment scenarios and presenting the implications of the response approaches (Netherlands Environmental Assessment Agency, 2021). Van Vuuren et al. (2019) applied IMAGE to build scenarios that show 60% increase in global food and energy needs, and 20% in water demand if no new global policies for resource efficiency are taken up.

These above-mentioned models are basically quantitative data driven, and less focused on possible scenarios. IMAGE, which focused on several scenarios development, specifically models human activities and their effects on ecosystem, which is out of the scope for this study. In this study, fuzzy cognitive mapping (FCM) was used instead, as the basis of system modelling, FCM is more focused on making relationships more obvious between multiple, interdisciplinary or socio-economic sectors, whereas, others tend to describe a single representation of relationality between nodes in the system.

Fuzzy cognitive mapping (FCM) – FCM is a graph-based and network-based analytical technique that helps to understand complex system coherently and organize concepts in semi-quantitative models (Obiedat & Samarasinghe, 2016). In FCM, relationships between these concepts can be dynamically coordinated in a way that brings meaning to the relationships between system elements. FCM can create economic, social or ecological scenarios around different components of a system, and also show the structural effects (positive or negative) of these "what if" situations on the components in statistical manner. FCM is also described as a simulation model that analyses the causality relationships of complex systems by presenting these systems as a whole system, thereby enabling experts to observe the results of scenarios before they really occur (Kosko, 1986). Different scenarios of the socio-ecological and economic effects of human activities can be observed using FCM and the earth's future capacity to endure, can be predicted (Olazabal & Pascual, 2016). This, in turn, can influence the kind of policy decisions to make (Solana-Gutiérrez et al., 2017).

There is a growing trend in nexus research toward combining qualitative and quantitative methods, as an integrated approach necessary for robust modelling, usually if the qualitative definition is generated in collaboration with local stakeholders (Sušnik & Staddon, 2021). A few number of studies have used FCM as a modelling tool for WEF nexus approach. Martinez et al. (2018) applied fuzzy cognitive mapping, originating from a qualitative social science knowledge, to identify local perspectives on WEF nexus linkages, improving the quantitative integrity of a formerly qualitative method to mapping a nexus. Purwanto et al. (2019) and Ziv et al. (2018) created causal models of the WEF nexus generated through fuzzy cognitive mapping to identify how different WEF actors perceive the water-energy-food interactions and their significances in attaining sustainability. Through a nexus viewpoint, a study in a semi-arid region of Austria collect the opinions of actors involved in nature conservation, agriculture, RE, tourism, water management, hunting and the civic society hunting in order to create a consolidated cognitive map (Kropf et al., 2021).

In their paper which evaluates WEF nexus for future studies, Sušnik & Staddon (2021) observed that many research use quantitative approaches to "quantify the nexus", and that these publications show that causal mapping is utilized at an initial point to understand the whole system design and the primary interactions in order to construct quantitative models as the most visible outcomes.

This section reviewed the water-energy-food (WEF) nexus framework and the system representation of nexus approaches. The next chapter will describe the methodology used in the research.

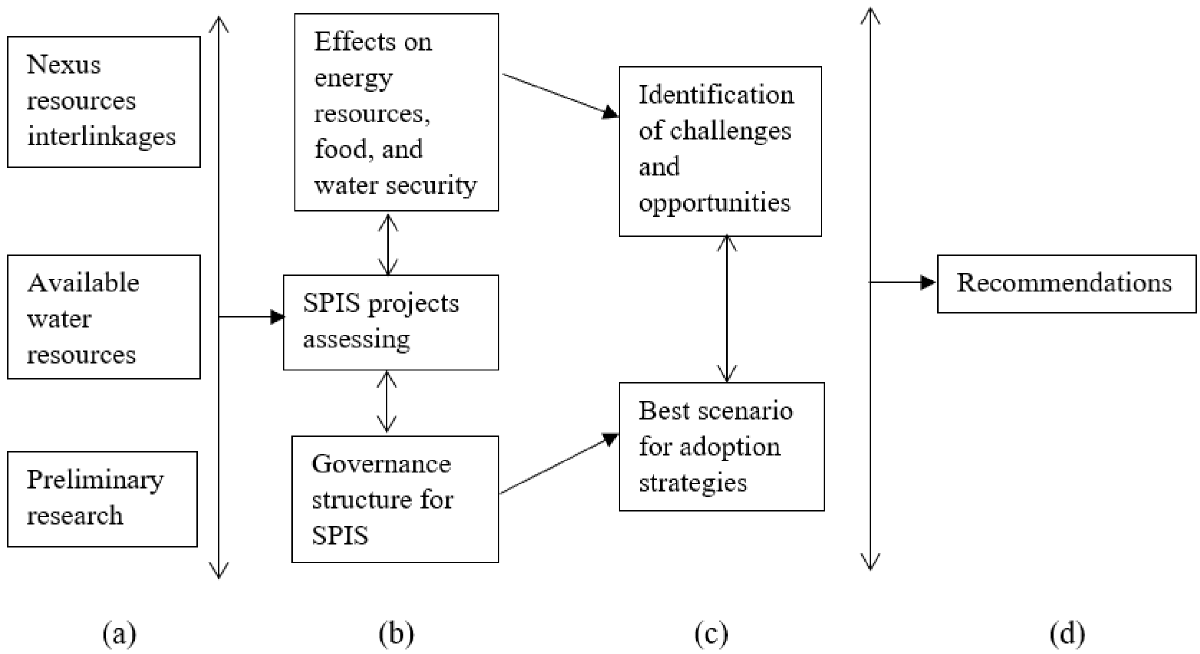
METHODOLOGY

This chapter describes the steps taken during this research and how the theories mentioned in the preceding sections are operationalized. It contains the research methods, data sources, and data collection. Then, the selection of projects and data analysis.

4.1. Research Design

4.1.1. Research Framework

A research framework which is adapted from Verschuren & Doorewaard (2010), was designed to show the overview of the steps that were followed to answer the research questions. According to the schematic representation in Figure 5, the first step (a) involved data gathering and thereby obtaining knowledge of current policies and water situation in the study area. The second step (b) involved the application of nexus approach to assess the SPIS projects. The third step (c) involved creating a system model of solar pump projects using fuzzy cognitive mapping (FCM), data analysis and reasoning. And the last step (d) entailed translating the results into proposals for feasible policies to improve the adoption of SPIS without stressing the groundwater resources.



(adapted from Verschuren & Doorewaard, 2010)

Figure 5. The Research Framework

4.1.2. Research Strategy

This study was based on desk research coupled with interviews to evaluate the proposed governance strategies. The strategy of this research required a case study approach to examine the selected SPIS projects (research objects) by utilizing qualitative and semi-quantitative methods to gather the needed data. Using data gathered from grey and scientific literature, the study identified and analysed the interlinkages between the nexus resources using the Water-Energy-Food Nexus approach. Linkages between concepts and variables identified during the desk research and interviews were analysed using fuzzy cognitive mapping (FCM), which form the basis for policy recommendations.

4.1.3. Research Unit

This research focused on solar-powered pump irrigation system projects in North Africa, their benefits and challenges as well as the project implementers as the unit of this research. Due to the availability of data, focus was directed to the case studies in Egypt. Fuzzy cognitive mapping is also a unit of the research.

4.1.4. Research Boundary

For the timely completion of this research and to ensure that the study objectives are achieved, the following research boundaries used are:

- Focus on solar-powered pump irrigation system as a promising agricultural technology being promoted by the government
- Focus on groundwater extraction for irrigation only
- Focus on projects only promoted by the government of the selected country and their effects on water, food and energy dimensions at the farm level

4.2. Research Methods and Data Collection

A preliminary document review was done to understand the present status of the adoption of solar pump irrigation systems (SPIS) in North Africa as well as the governance structure in place. SPIS projects in Egypt were then identified. The implementation process and the status of these projects were assessed by reviewing government documents, international organizations' databases, and policy documents.

The previously described framework and theory were used to analyze the effects of these projects on the nexus resources. This further clarified the opportunities and benefits of these projects and more generally, the promotion of the technology. Comparison between solar pump and diesel pump for irrigation are also established through the desk study.

The methods used for this research are structured literature review and desk study, fuzzy cognitive mapping, and expert interviews. These methods gathered inferences from prior publications and experiences of experts to propose policy options and predict future outcomes of the continual adoption of solar pump irrigation system. The rationale for using these methods is described in Table 2.

Table 2. Data sources and collection methods

Sub-Question	**Information required to answer the question**	**Data source and collection methods**
What are the water resources available, the environmental regulations in place, and how do they influence the adoption of SPIP?	Water resources and irrigation policies	* Secondary data * Documents from desk study and structured review
What are the effects of solar pumping on water, food and energy resources?	Opportunities, benefits and challenges of using solar pumps at the farm level	* Secondary data * Documents from desk study and structured review
How can the in-field context be represented in a systematic way to model policy scenarios?	Concepts associated with the solar pump irrigation projects and irrigation terminologies, to create a mind map	* Primary data - Semi-structured interview with experts * Secondary data - Documents from desk study, structured review

		* Fuzzy cognitive map scenarios
How might SPIS be successfully adopted without overexploitation?	* Importance and responsibilities of solar irrigation stakeholders * Significant factors that increase groundwater abstraction	***** Primary data - Semi-structured interview with experts * Secondary data - Documents from desk study, structured review, and Fuzzy cognitive map scenarios
What governance strategies can be proposed to improve the rate of water withdrawals using SPIS?	Possible policies that should be enforced and improved	* Primary data Semi-structured interview with experts * Fuzzy cognitive map scenarios

4.2.1. Projects and experts selection

Experts were selected based on availability, experience and willingness to provide relevant information. The project case studies were selected through the review of grey literature. The search keywords are "Solar pumps irrigation in Egypt", "Solar-powered irrigation projects in Egypt". The selection criteria for the projects are;

- Projects sponsored by the government bodies in partnership with international organizations
- Projects with documents containing their descriptions, design and implementation processes and lists of stakeholders
- Projects available in English language
- Projects with contact information and willingness of project Managers to grant an interview

The list of potential solar pump irrigation system projects with brief description and status is given below (Table 3).

Table 3. List of experts and potential SPIS projects in North Africa

Project name	Description
Clean-tech entrepreneurship and market development project in Egypt (IFC, 2020b)	International Finance Corporation (IFC) partnered with Agricultural Bank of Egypt (ABE) to help farmers access funding for farmers to purchase and switch to solar pumps for irrigation at affordable prices, to save them US $875 million annually in diesel fuel costs
Desert-to-power Initiative (budget-US$ 21.781 million) (AFDB, 2021)	The project aims to increase the replacement of diesel-powered pumps with solar-powered by installing 1,170 solar PV pumps in North and West Kordofan, Sudan. Duration is from 2019-2024 and sponsored by African Development Bank
Solar water pumps for sustainable agriculture in Sudan (UNDP, 2019)	The Korea International Cooperation Agency (KOICA) (US$6.4 million) and United Nations Development Programme (UNDP) (US$0.6 million) are financing the project between 2019 - 2023. The project aims to directly help 450 small and medium farmers in northern Sudan.
Promoting the development of photovoltaic pumping system for irrigation	A 4-year project, implemented between 14 October 2016 and 13 October 2020, and co- financed by the Government of Morocco (41,837,000 USD), private banks (up to 28,966,000 USD), Global Environment Facility (up to 2,639,726 USD) and UNDP (up to 100,000 USD) co-financed the 4-year project. The aim of the project is to establish a framework conducive to the development of solar pumping and the creation of favourable conditions for its success.

Promoting the use of solar pumps in Western Egypt for irrigation (Tawfeek, 2018)	The project aims to support Egypt's transition to renewable energy source by providing funds for farmers to switch to affordable irrigation system through solar power. FAO signed an agreement with the Egyptians government for a grant of US$276,000 to promote the use of solar pumps in Western Egypt for irrigation
Projects with positive response interviewed and examined	
- Clean-tech entrepreneurship and market development project in Egypt - Promoting the use of solar pumps in Western Egypt for irrigation	
Expert	**Date interviewed**
Project Manager A	16th May, 2022
Project Manager B	31st May, 2022
Agricultural Water Management Expert and SPIS Researcher A	2nd June, 2022
Agricultural Water Management Expert and SPIS Researcher B	20th May, 2022
WEF Nexus Researcher A	27th May, 2022
WEF Nexus Researcher B	6th June, 2022
Agricultural Water Management Expert and SPIS Researcher C	8th August, 2022

Note: Photos in Appendix C

What are the water resources available and the environmental regulatory in place, and how do they influence the adoption of SPIS? (descriptive)

4.2.2. Structured review and desk study

The structured review and desk study was carried out using Google Scholar and Web of Science databases to assess peer reviewed publications and articles. Desk research of grey literatures was used to obtain country-related information about environmental policies, water resources and amount available. Keywords used include "water resources in Egypt", "water policies and governance" and "solar pumps and irrigation policies in Egypt". The WEF framework will also provide insight about the amount of water being used for agriculture in relation to crop water requirement and hydro-electricity generation.

What are the effects of solar pumping on water, food and energy resources?

4.2.3. Desk research

With the use of google scholar and web of science databases, relevant peer reviewed publications and articles were identified. Information regarding the opportunities, benefits and challenges of using solar pumps irrigation in semi-arid region were obtained. This information was classified using the WEF nexus interlinkages. SPIS projects documents, grey literatures and official websites for statistical databases such as FAOSTAT and World Bank were also used. Keywords used in the document search include "Benefits, trade-offs and opportunities of solar pump irrigation", "nexus interlinkages for solar irrigation", "groundwater overexploitation and stakeholders" and "Diesel pumps and solar pumps for irrigation". Data obtained aid the general description of the contributions of solar pump irrigation to sustainable development.

How might SPIS be successfully adopted without overexploitation?

4.2.4. Semi-structured interviews

Semi-structured interviews with projects implementers, agricultural water management experts and solar irrigation researchers were conducted. Projects were identified through internet search and review of reports and documents. The interviewees were contacted through emails. Questionnaires with open questions was prepared. The questions were themed and structured such that information about irrigation policies, available water resources, implementation process, outcomes so far, opportunities and challenges, important factors during the adoption of solar pump irrigation system and the way forward, were obtained. The purpose of this is to gather information about implementation process of solar pump irrigation system projects and also obtain opinions and evaluate the proposed strategies for feasibility and credibility.

4.2.5. Fuzzy cognitive mapping

Concepts and factors were identified through content analysis of scientific literatures and interviews of experts. Causality relationships between concepts were established and edge weight assigned in a fuzzy manner with confirmation from experts. 'What if' scenarios were developed to understand the dynamics of solar pump irrigation systems and to understand the concepts and factors that should be emphasized and incorporated in order to address groundwater overexploitation. These were translated into policy options.

How can the in-field context be represented in a systematic way to model policy scenarios?

4.2.6. Interviews and desk research

Selected experts were interviewed and relevant concepts were identified which was used in creating the fuzzy cognitive mapping. Variables and their connections with each other were also establish through literation review of documents. Report and scientific articles were reviewed in order to obtain the rationale behind the established connections between variables.

4.2.7. Fuzzy cognitive mapping

A mind map that shows concepts and their interactions was created using the mental modeler software. Causality relationships between concepts were established and weights were assigned in a fuzzy manner with confirmation from experts.

What governance strategies can be proposed to temper the rate of agricultural water withdrawals using SPIS?

4.2.8. Expert interviews

Experts in solar irrigation were interviewed through open interviews (Appendix A), based on their experience with solar pump irrigation system, their interactions with farmers and their involvement with solar pump projects. The interviewees were contacted through emails. Suggestions for better sustainable use of groundwater resources and governance of solar pump irrigation systems, as well as the results obtainable from the suggested strategies were gathered from these discussions.

4.2.9. Fuzzy cognitive mapping

'What if' scenarios were developed to understand the dynamics of suggested governance strategies with the present situation regarding groundwater withdrawals. The results were used to predict policy options that could be incorporated.

4.3. Design system representation of SPIS situation

In this study, the FCM analysis approach used was adapted from the FCM steps for ecological models described by (Özesmi & Özesmi, 2004) and the Mental Modeler Software (modelling tool) (https://www.mentalmodeler.com/, n.d.) as applied by (Gray et al., 2013) for adaptive environmental management

i. **Creating a mind map:** Concepts, variables and factors associated with the use of SPIS and the causal relationship between them were identified texts and data from desk research (scientific literatures, project documents) and open interviews. Individual interviews identified concepts that they recognised as being important in the design, implementation and adoption of solar pump irrigation system. Resultant mind-maps were aggregated into a single-represented fuzzy cognitive map. The scientific database is used to find articles to populate variables (Jetter & Kok, 2014) and linkages, using the following search keywords; "Solar pump irrigation and food security", "Solar pump irrigation and water security "Solar pump irrigation in arid region", "Solar pump irrigation and climate change", "Solar pump irrigation and rural development", "Solar pump irrigation and farmer's livelihood", "Solar pump irrigation and economic viability", "Solar pump irrigation and groundwater resources", "Solar pump irrigation and water policies" and "Solar pump irrigation and WEF nexus" (Table 8).

ii. **Assigning numerical strength to causal relationship:** The existence of a connection between variables, identified in the literature in step (i), is translated into a square numerical matrix by the Mental Modeler. In this causality matrix W_{ij}, the concepts are repeated as rows and columns, and therefore each element of the matrix represents the strength of connection (interaction) between concept of row i and concept of row j. A numerical strength between -1 and 1 is assigned to represent the causal increase or decrease between concepts, and their verbal expression is presented in Table 4. The degree of interactions were decided based on the information obtained from literature review and interviews; and adjustments to values were cross-checked by key experts.

Table 4. The ranges of strength of interactions(Gray et al., 2013; Jetter & Kok, 2014; Kok, 2009)

Linguistic expression	**Semi-quantitative values**
Very High connection	0.8-1
High connection	0.55-0.75
Medium connection	0.3-0.5
Low connection	0.1 – 0.25
No Connection	0

Note: Negative connections are coded as the inverse of positive connections

iii. **Building scenarios:** Using the mental modeler software, scenarios were developed to explore the current situation and the potential modifications that could be done in the system to improve the sustainable adoption of solar pump irrigation system. First, preferred state was identified based on the problem statement. Three scenarios were built using the hyperbolic tangent function to portray different situations including: a baseline scenario to represent the present situation, a negative scenario that shows the system state when things go wrongly and a positive scenario that addresses the possible pitfalls of SPIS. The hyperbolic tangent hyperbolic function has values with wider range of -1 to 1 which allows the worst-case scenarios to be evenly represented by strong negative values (Kokkinos et al., 2020). Scenario assumptions were done by increasing or decreasing some of the components to achieve the preferred state scenario (Table 5). The graphical outcomes from the scenarios were further analyzed to understand the effects of the changes done in the system.

iv. **Drawing conclusions from the result:** Based on this analysis and using scientific data, ranges of policy options for achieving the preferred state in real life were proposed. Policy instruments in form of regulatory instrument (well permits), financial incentives (energy feed-in tariffs) and techno-regulation (smart irrigation) are adjusted to indicate the trend and direction of results. In addition, the combination of policy options that shows the highest tendencies of output is indicated and used to draw policy conclusions.

The purpose of using fuzzy cognitive mapping is to identify probable variables that are important in the adoption of SPIS and give direction towards possible policies after identifying the drivers (variables that are affecting others but they themselves are not affected), receivers (variables that are affected by others but they themselves are not affecting any variable), ordinary (variables that are neither receivers nor drivers), indegree (number of ties entering a variable), outdegree (number of ties leaving a variable) and degree centrality (Variable with the highest number of ties).

The conditions for the scenarios were decided upon after taking into account the knowledge gained from the interviews with projects/experts (to be presented in the results section). Policy-options proposals for solar pump irrigation system were made based on desk research and system model of the best scenario.

Table 5. Overview of Scenarios

Scenario	**Preferred State**	**Percentage increase/decrease**
A	Increased well permits	50%
	Increased smart irrigation	50%
B	Increased Energy feed-in tariff	50%
	Increased Water-Energy-Food sectoral collaboration	50%
C	Reduced irrigation policies	50%
	Reduced financial aids	50%

4.4. Data Analysis

The data obtained from desk research, literature review and expert interviews were used to obtain information about the experiences of farmers, project managers and government agencies in the application and adoption of SPIS through triangulation of data from various sources and content analysis. The interviews were also analysed based on the question theme through triangulation of data. For the purpose of this study, "triangulation has been adopted in social science in the study of the same phenomenon through applying and combining several data sources, research methods, investigators, and theoretical schemes" (Wang & Duffy, 2009). Content analysis is a research tool used to determine the characteristics of concepts or topics of a given qualitative data (Wang & Duffy, 2009).

4.5. Ethical Considerations

This research guarantees transparent and independent view without any commercial relationship that could infer potential conflict of interest. Data were gathered from peer reviewed literatures, publicly available documents and interviews with experts which complies with the ethical standards set by the ethics committee of the Faculty of Behavioural, Management, and Social Sciences of the University of Twente. Also, an informed consent form (Appendix B) which allows interviewees to exercised their rights was used during the interview.

RESULTS

This section describes the outcomes of the interview with experts and projects, as well as the results of the fuzzy cognitive mapping, thereby resolving the research questions of this study.

PROJECTS PROFILE

Clean-tech entrepreneurship and market development project in Egypt (IFC, 2020b)

With the support of the Agricultural Bank of Egypt (ABE), the International Finance Corporation (IFC) provides funds to Egyptian farmers so that they could afford to switch to solar pumps for irrigation, saving an estimated $875 million per year on diesel fuel. Since the ABE caters for about 4 million farmers, the scheme aims to reach as much. According to the interview with Project Manager A, market surveys were carried out to determine the profitability of the project and consultations with water resources agency provides information on available water resources and relevant stakeholders. Farmers were also selected based on farm size and evidences of well permits.

Promoting the use of solar pumps in Western Egypt for irrigation (Tawfeek, 2018)

The duration of this project is 3 years (2019-2021) goal of this initiative is to help Egyptian farmers make the switch to a solar-powered, lower-cost irrigation system and so aid the country's clean energy transition. The Food and Agriculture Organization (FAO) provided a grant to the Egyptian government in the amount of $276,000, used to encourage the use of solar pumps in Egypt’s western desert for irrigation purposes. Farmers and Water User Association members were also given training on how to operate and maintain the system. The FAO provided technical and financial support while the Egyptian government chose the participating farmers. This project aimed decrease greenhouse gas emissions and provide affordable, clean energy to farmers.

WHAT ARE THE WATER RESOURCES AVAILABLE AND THE ENVIRONMENTAL REGULATORY IN PLACE, AND HOW DO THEY INFLUENCE THE ADOPTION OF SPIS?

5.1. Available water resources

Generally, Egypt has limited water resources consisting both conventional and non-conventional sources. The major water resources include Nile River (Abd Ellah, 2020; Swain, 2011). Other sources include groundwater (underground aquifers of Nile valley and Delta, the

Nubian Sandstone Aquifer in the Western Desert, the Sinai Peninsula and other minor aquifers mainly around the coastal and Delta regions), rainwater, reuse of drainage wastewater (agricultural drainage water and treated waste water) and seawater desalination, which all together sum up to a total of 76.4 billion cubic metres (BCM) as at 2015 (Figure 6) (Table 6) (Abd Ellah, 2020; EEAA, 2018; El-Rawy et al., 2020). The Egyptians water consumption mainly comprises of agriculture, domestic and industrial purposes, and also include hydropower generation (Fobissie & Shalaby, 2021), and agriculture sector have the highest consumption (Mostafa et al., 2021).

Table 6. Water resources in Egypt (CAPMAS, 2016; EEAA, 2018)

Water input	Million m^3 per year
Share from Nile river	55,500
Underground water in Nile valley and Delta	6,900
Reuse of agricultural drainage water	11,700
Reuse of treated wastewater	1,300
Rain and floods	900
Seawater Desalination	100
Total	76,400

5.2. Agricultural water resources

5.2.1. Surface water resources

Nile river is the most abundant surface water available in Egypt , covering an area of up to 2.9 million km^2 and it's 6,695 km in length (Tadese, 2020). Nile water is the main freshwater resource in Egypt with an apportioned share of 55.5 billion cubic meters (BCM) per year (Figure) according to the treaty agreement with Ethiopia and Sudan, and this represents up to 97 percent of the available renewable water resources (EEAA, 2018; El-Rawy et al., 2020; Gad, 2017). In the interview with project Managers A and B also confirms river Nile ss the main source of surface water for the Egyptians for many years, explaining that most agricultural activities and majority of the Egyptian population are concentrated along its bank. “For most of the farms that have been cultivated around the river Nile, they have been using the flood irrigation for decades” (Project Manager B).

Agriculture consumes up to 39.2 billion cubic meters/year alongside its irrigation canals of 33,550 km long (AbuZeid, 2020). As an hyper-arid region, rainfall is not a reliable source of water. Annual rainfall ranges from 0-200mm depending on the location and the amount of rainwater is around 1.3 billion cubic meters/year which has been projected to decrease in the coming years (Abd Ellah, 2020; AbuZeid, 2020). Rainfall is limited to the coastline along the Mediterranean in winter (Gad, 2017).

5.2.2. Groundwater Resources

Nile aquifer, desert aquifer and coastal aquifer are the main source of groundwater resources in Egypt. Nile and Desert aquifers are difficult to recharge especially the deep desert groundwater which are not renewable (Gad, 2017). The Nile aquifers in the Nile delta and valley are fed by the infiltration of Nile water and excess irrigation water (Gad, 2017). Other factors influencing groundwater are rainfall and drainage water. Freshwater of the coastal aquifer is formed by rainfall at the coastline, although it is vulnerable to salt water intrusion and climate change affects the recharge rate of all these aquifers (Abd Ellah, 2020). “About 2.1 BCM/year are withdrawn from non-renewable groundwater aquifers for agriculture purposes. In addition, about 5.5 BCM/year are abstracted from return groundwater recharge within the Nile Valley and Delta aquifers” (AbuZeid, 2020). Interviews with Project Manager A and B confirmed the use of solar pumps to access groundwater in the off-grid and desert region.

5.2.3. Reuse of agriculture drainage and treated wastewater

According to an interview with Project Manager B, the Egyptian government are placing more importance on finding alternative sources of water such as desalination and water reuse, especially with the construction of the Ethiopia dam on the river Nile. The reuse of treated drainage water is one of the new source that provides a reasonable amount of water for the Egyptians (Abdin & Gafaar, 2009). Although this is a non-conventional source that cannot be added to the amount of fresh water available in Egypt. However, this water recycling method improves water use efficiency and saves water (Gad, 2017). In 2013, quantity of water reused amounts to about 13 BCM. Most of the reused water is the water drained from agricultural and irrigated land, which then returns to the Nile (Abd Ellah, 2020). “About 9.31 BCM/year of agriculture drainage is being reused in agriculture, in addition to about 4.19 BCM/year of treated wastewater which is directly or indirectly reused in agriculture" (AbuZeid, 2020).

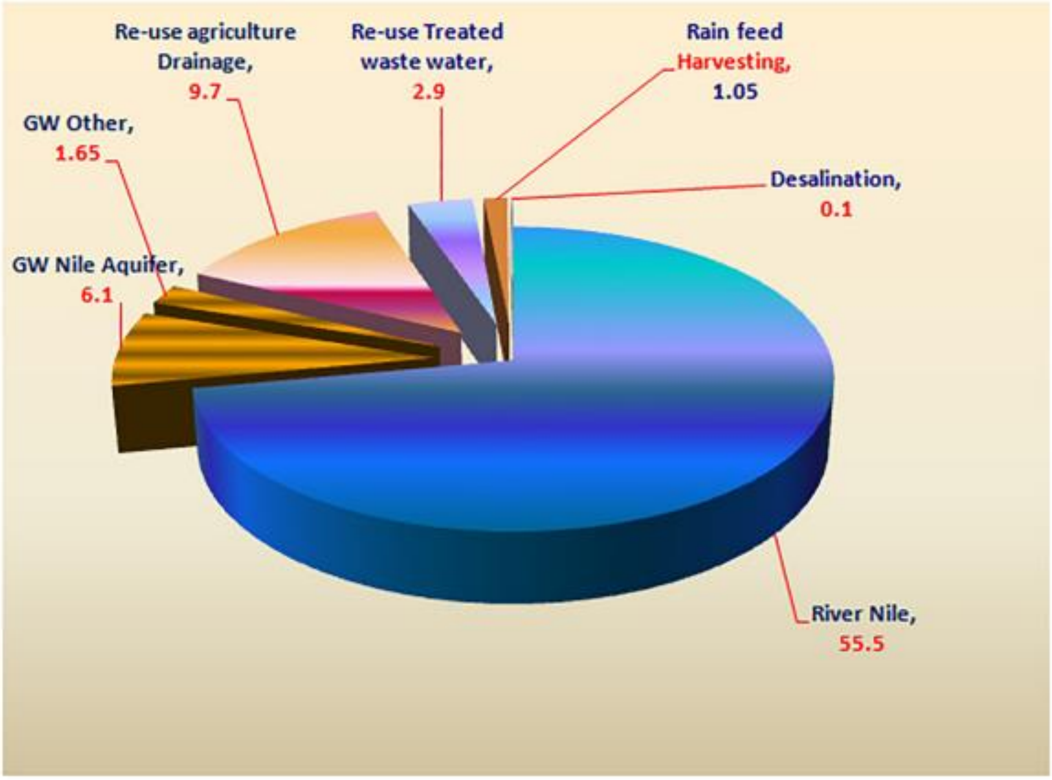


Figure 6. Water resource availability in Egypt (in billion cubic metres) (Abd Ellah, 2020, *p.2)*

5.3. Environmental Regulatory

The main environmental policies concerned with solar pump irrigation systems are land policies, water policies and energy policies. Land policies in Egypt are centred around land reclamation and fragmentation, such that strategies are directed towards efficient use of the available arable land, reclamation of land through the irrigation of desert areas, and the improvement of irrigation system for higher agricultural productivity (Tellioglu & Konandreas, 2017). The government policy for land fragmentation started in 1952, stating 190 feddans (feddan is a unit area and one feddan equals to 4,200 m^2 or 0.42 hectare) as the maximum land that can be owed per person which was later reduced to 100 feddans per person in order to help small scale farmers and promote equity (El-Nahrawy, 2011; Tellioglu & Konandreas, 2017). The present tax law provides incentives that would discourage land sales or combining, and also exempt owners of lands less than, 2 feddans from paying taxes. Land reclamation in Egypt is one of the strategies employed to promote agricultural development by expanding agricultural land through reclaiming desert regions (Tellioglu & Konandreas, 2017). Reclaimed lands (Deserts converted into new agricultural lands) are usually achieved by irrigation.

The Egyptians water policy (EWP) aims to improve water quality, reduce water pollution, mitigate groundwater withdrawal and encourages drainage water reuse. Present policies according to the national water resources plan (NWRP) adopted integrated management approach which is supposed to foster coordination among governmental institutions and water users association. Both structural and non-structural measures are stipulated. These include; "rehabilitation of irrigation structures", "improvement of the irrigation system", "installation of water level monitoring devices linked to telemetry systems", "improvement of the drainage system", "increased exploitation of deep groundwater", "establishment of the irrigation advisory service and the expansion of the water users association (WUAs) for ditches and irrigation canals" (Abdin & Gafaar, 2009), "the establishment of water boards on branch canals, the promotion of public awareness programs as well as the involvement of stakeholders" (Abdin et al., 2011).

Egypt's energy policy reform programme is aimed at achieving an energy mix comprised of 40% renewable sources by 2035 (UNDP, 2022). Solar projects are being designed and implemented all over the country since the country has an abundance of solar potential. Since 2014, the Egyptian government has been reducing fuel subsidies (diesel by 64 percent) which has led to the increase in the prices of petroleum products (WRI, 2021). This in turn, strengthened the market for solar pump irrigation system. Project Manager A also affirmed since 2026, the Egyptians government had started removing diesel subsidies which hiked the diesel prices, thereby accelerating the acceptance of the SPIS project.

The Country Programming Framework (CPF) Outputs for Egypt between 2012 and 2017, that aligns with solar pump irrigation systems are "Priority Area B: Improving productivity and efficiency in the agricultural sector, especially on irrigation modernization; Priority Area D: Conserving natural resources and adapting to impacts of climate change" (FAO, 2020). Solar pump irrigation systems are being encouraged in agricultural sector in Egypt's framework of national action plans against climate change, as a form of mitigating greenhouse gas (GHG) emissions in the sector (FAO, 2020). "Egypt included climate smart agriculture (CSA) in its NDC adaptation contributions, which allows farmers to increase agricultural production while enabling them to adapt to climate change" (Fobissie & Shalaby, 2021).

5.4. Comparison between diesel pump irrigation systems and solar pump irrigation systems

The differences between diesel-powered irrigation system and solar-powered irrigation system are presented in Table 7.

Table 7. General comparison between diesel pump irrigation systems and solar pump irrigation systems

	Diesel Pump Irrigation System	Solar Pump Irrigation System	References
Components/ Technical	- Components include diesel generator, pump, pump-motor, controller/inverter -Installation is faster and easier -Efficiency of a diesel generator reduces with time, although it works continuously at certain efficiency on both cloudy and sunny days	- Components include photovoltaic array, pump, pump-motor, controller/inverter - Installation and repair usually require skilled technicians - Power produced is constant throughout life span as long as solar panels are still intact, however, efficiency depends on the sun intensity, panel angles, size of PV panels and day-type (cloudy or sunny day) - Aids technical empowerment of locals - Increases the rate of rural electrification	(Abu-aligah, 2011; Al-Smairan, 2012; Chandel et al., 2015; Kelley et al., 2010; Meah et al., 2008; Odeh et al., 2006)
Life Span	- 5-10 years	- 10-20 years	(Abu-aligah, 2011; Chandel et al., 2015; Kelley et al., 2010; Meah et al., 2008)
Climate requirement	- No climate or weather conditions are required for use	- Requires solar radiation which strongly depend on latitude and climate	(Abu-aligah, 2011; Armanuos et al., 2016)

Economic	- High diesel cost - High maintenance and operating cost due to regular maintenance of generator - Higher life cycle cost considering present value, capital cost, fuel, transportation, replacement, operating and maintenance cost	- Free energy from the sun - No fuel cost - Low maintenance cost and no operating cost - High investment cost but decreases significantly when supported with financial aids (about 22-56% of diesel pumps' cost) - More lucrative for water-intensive crops	(Al-Smairan, 2012; Dadhich & Shrivastava, 2018; Hossain et al., 2015; Kelley et al., 2010; Khan et al., 2014; Meah et al., 2008; Odeh et al., 2006; Parvaresh Rizi et al., 2019; Xie et al., 2021)
Environmental	- Noise pollution - Air pollution, contributing to carbon emissions	- Less noise for health reasons - Use of renewable energy, thereby reducing dependency on fossil fuel - Facilitates the shift towards climate-smart agriculture	(Al-Smairan, 2012; Khan et al., 2014; Meah et al., 2008; Odeh et al., 2006)
Limitation	- Expensive to use in remote areas due to cost of fuel transportation	- Suitable for remote water pumping, where either electric transmission lines are unreachable or diesel fuel is high - Water can only be pumped during the day since the energy source is from the sun - Challenges associated with solar panel disposals in the future e.g. pollution of water resources	(Al-Smairan, 2012; Hossain et al., 2015; Meah et al., 2008)

In the life cycle assessment (LCA) of diesel-powered and solar-powered irrigation system carried out by (Armanuos et al., 2016), it was discovered that the environmental impacts of diesel pumps for groundwater pumping on resources depletion and human health is far higher than that of solar pumps. Nevertheless, for better comparison, a complete cradle-to-grave LCA carried out shows the negative environmental impacts of solar systems. Silicon-based PV exhibit higher negative impact, but higher efficiency and longer life span than organic solar PV (Tsang et al., 2016). Therefore the type of solar panels and recycling processes determines the advantages of solar pumps over diesel pumps. “The potential of increasing the ecological advantage of solar pumping systems compared to diesel powered pumping systems even further lies in increasing the efficiency and lifetime of OPVs and in the implementing of full-scale silicon recycling processes, which are right now not existing” (Tsang et al., 2016).

5.5. Water-Energy-Food Security Nexus

One of the most crucial benefits of solar pump for farmers is the assurance that there is water available to continue their agricultural activities. Food security is already in a dangerous spot in Egypt (Ramadan, 2015) and “as a strategic framework for food production, Egypt is taking positive measures to employ solar energy as a renewable energy source for water pumping in reclaimed desert regions” (El-Bably & Abd El-Hafez, 2019). Solar pump irrigation system can improve food production by using sustainable irrigation to provide prompt irrigation. However, this food challenge should not be prioritized at the detriment of the nation's water security, since any attempt to ensure food security is usually intertwined with water security discourse.

Due to the substantial amount of rural Egyptians and their reliance on agriculture, it is crucial to employ the most efficient and water-conserving irrigation methods. As solar pump is relevant for food production, (Aklan & Lackner, 2021) mentioned that the most ideal sites for solar-powered pumps are regions which have yearly precipitation between 300 and 400 millimetres. However, more than 90 percent of Egypt experiences mean annual rainfall of less than 100mm/year (Abdel-Shafy et al., 2010), contributing to the Nation’s long-standing dependence on groundwater resource. Even though Alexandria (city located along Mediterranean sea coast) (World Bank, 2020) experiences annual rainfall of almost 200mm/year and Rosetta (city located at the Nile Delta) encountered the highest annual rainfall of 441.1mm in 2020 (Abdel-Shafy et al., 2010). About 50-60 percent of Egypt’s food supplies is supported by import and Wheat imports from Egypt are among the highest in the world. To lessen Egypt's reliance on foreign food imports and improve domestic food production, the government seeks to expand reclaimed land through the use of solar pump irrigation systems and extend the cultivation of maize and wheat (El-Bably & Abd El-Hafez, 2019).

Energy is a very essential input for food production. Solar-powered pump irrigation system is introduced as one of the climate smart agriculture (CSA) practices that supports food security in a dynamic climate (Fawzy & Shedeed, 2020). Therefore, the adoption of SPIS is a bid towards taking advantage of the abundant sun radiation and achieve the goal of 40 percent renewables in 2035 (FAO, 2020; UNDP, 2022). Small scale farmers who own solar pumps can also have access to affordable energy for other agricultural and food operations (IRENA & FAO, 2021). Consequently, the promotion of SPIS can provide basic services such as domestic water and electricity to a large populace that may not initially have access to them (Aklan & Lackner, 2021).

HOW CAN THE IN-FIELD CONTEXT BE REPRESENTED IN A SYSTEMATIC WAY TO MODEL POLICY SCENARIOS?

5.6. Mind Map

The fuzzy cognitive mapping is represented as a mind map in Figure 7 as computed by the mental modeler software. This indicates the concepts related to solar pump irrigation projects as mentioned by interviewees with connections showing the direction of influence and relationships. Table 8 shows the justification for each relationship which represents the baseline scenario. The outcomes of negative and positive scenarios will be represented later in the chapter.

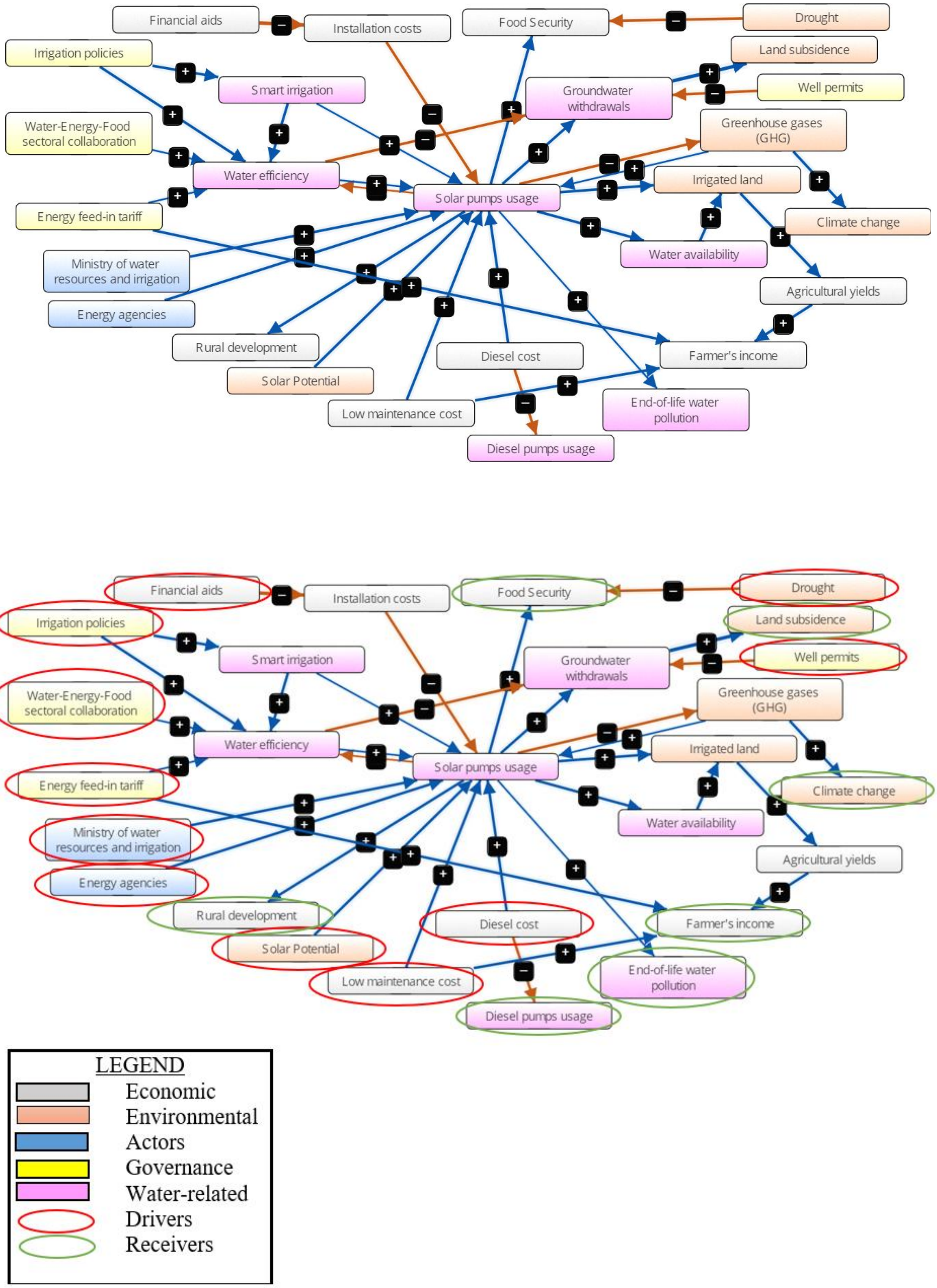


Figure 7. Mind map and components (Baseline scenario)

Table 8. The justifications for the strength of interaction of the links shown in the FCM

Source Components	**Linked Components**	**#**	**Justification (from literature and interviews)**
Solar pumps usage	End-of-life water pollution	+0.45	Although this relationship is not yet prominent, water management experts thinks it is important to plan for the end of life of solar panels considering the rate of adoption of solar pumps, because chemical elements of PV panels can leach into water bodies
Solar pumps usage	Rural development	+0.5	Solar pump irrigation is gaining prominence among farmers in rural areas, as it ensures energy accessibility for agriculture, and for other users for which reliable energy is a challenge or people living in areas where cost of diesel is high (FAO, 2020). "This project focus is in off grid areas, so areas that are not covered by the electrical network and in these areas, the main benefit I think in this case would be, Lower costs for the farmers, higher savings" (Project Manager A)
Solar pumps usage	Water efficiency	-0.2	Solar pump may promote water efficiency when coupled with drip irrigation, otherwise, it could negatively affect water efficiency (WEF Nexus Researcher A). Also the use of solar pumps has increased awareness on flood irrigation consequences
Solar pumps usage	Food Security	+0.8	"…we can have more irrigation, more water for irrigation with expanding the agricultural land for farmers…having more food production, better livelihoods for these families" (Project Manager B)
Solar pumps usage	Water availability	+0.5	If farmers have access to such free energy, they could be promoted to pump more water for their crops and earn more income (Agricultural Water Management

			Expert and SPIS Researcher A). "…we can have more irrigation, more water for irrigation…" (WEF Nexus Researcher B)
Solar pumps usage	Greenhouse gases (GHG)	-0.6	The replacement of diesel pump with PV-operated pumps will help create a cleaner environment (IFC, 2020a). The use of solar-powered water pump irrigation reduces the amount of carbon dioxide (CO2) released into the atmosphere by agricultural activities (Meah et al., 2008)
Solar pumps usage	Irrigated land	+0.7	Through the project that provides financial products for the purchase of solar pumps, farmers will be able to increase irrigated farmlands (IFC, 2020a)
Solar pumps usage	Groundwater withdrawals	+0.5	Free power without incentives to limit usage can result to more groundwater pumping and reducing water levels, in agreement with an interview with a SPIS expert and researcher. "So you will save energy but at the same time solar pumping will allow you to extract more water which may affect sustainability of groundwater resources" (WEF Nexus Researcher A)
Installation costs	Solar pumps usage	-0.75	An interview with a WEF policies researcher reveals that a 70 – 80% subsidy scheme provided by government had rapidly declined, thereby making it easier and viable for farmers to adopt solar irrigation systems. There are also projects which involve the allocation of loans to farmers, which can be repaid conveniently over a certain period of time (IFC, 2020a)
Well permits	Groundwater withdrawals	-0.7	For the solar projects, one of the criteria used to select farmer's participation is the issuance of well permits which is necessary to ensure that illegal wells are not

			dug up in unsuitable locations (Project Manager A). However, such documentation takes a long time to process, thereby affecting the progress of the project
Irrigation policies	Water efficiency	+0.8	Irrigation policies including the use of sprinkler and drip irrigation methods improve water efficiency (Senol, 2012). “Policies that modify economic parameters can motivate farmers to choose crops and irrigation methods that are consistent with public goals” (Wichelns, 2010)
Irrigation policies	Smart irrigation	+0.8	The development and amendment of policies is encouraging the use of smart irrigation comprising of soil moisture data to determine the irrigation requirement of certain farm land and the installation of drip irrigation techniques (DIT) (Rezk, 2016)
Drought	Food Security	-0.8	As an arid region, Egypt is at risk of suffering from climate-induced impacts such as drought, which adversely affect food supplies, especially with the continuous increase in population (Abdelfattah, 2021)
Diesel cost	Solar pumps usage	+0.55	“For the farmer it's lower cost energy and accessibility to energy…” (Project Manager A). Generally, in Egypt, the double increase in diesel cost has accelerated the switch to solar pumps irrigation among farmers, especially those in remote areas (Parvaresh Rizi et al., 2019)
Diesel cost	Diesel Pumps Usage	-0.7	“It's less of an effort because they need to go and get the diesel and there's always an issue of availability…the diesel powered pump requires a lot of upkeep and operational maintenance. So it's not just a matter of the cost of the diesel, it's a cost of the oil and the maintenance, which is rather significant cost

			actually and being able to save on that as well and spare themselves that hassle" (Project Manager A)
Water efficiency	Solar pumps usage	+0.2	Because solar pump helps to spread the awareness of drip irrigation. Hence the need for water efficiency through smart irrigation increases the promotion of solar pump irrigation system (Agricultural Water Management Expert and SPIS Researcher A and B)
Water efficiency	Groundwater withdrawals	-0.5	Efficient agricultural water reuse and the treatment of wastewater provides quality water for agricultural activities, thereby reducing reliance on the already stressed groundwater resources (Frascari et al., 2018)
Water availability	Irrigated land	+0.7	"…we can have more irrigation, more water for irrigation with expanding the agricultural land for farmers…" (WEF Nexus Researcher B). In Egypt, desert land are reclaimed for agriculture and other purposes through irrigation (Tellioglu & Konandreas, 2017)
Ministry of water resources and irrigation	Solar pumps usage	+0.5	Project implementation team had some Consultations with the ministry to ensure that the project doesn't conflict with any plans from the Ministry, and the team was supported in the identification of stakeholders (Project Manager A)
Energy agencies	Solar pumps usage	+0.8	The Ministry of Electricity and Renewable Energy hold a mandate to assist to government to achieve "20 percent clean energy by 2022, and 37 percent clean energy by 2035", therefore, building the largest solar power park and advocating for farmers to switch to solar pump irrigation are some of the strategies being employed (Reda, 2019)

Agricultural yields	Farmer's income	+0.7	“Another issue that affects the return on investment is the size of the land, the larger the land, the quicker it is ” (Project Manager A)
Greenhouse gases (GHG)	Solar pumps usage	+0.25	The need to achieve 37% clean energy in order to reduce greenhouse gases emission and attain climate smart agriculture has increased the utilization of solar pump irrigation, thereby promoting such projects (FAO, 2020; Reda, 2019) (Project Manager A and B)
Greenhouse gases (GHG)	Climate change	+0.7	The largest contributors to global warming are the greenhouse gases emissions (Elbasiouny et al., 2020). The rise in temperature in arid regions exacerbate the impact of climate change on the water resources of such region (Mostafa et al., 2021)
Irrigated land	Agricultural yields	+0.6	Farmers, through the free source of energy solar pumps, will be able to irrigate more lands. Hence, more yields (IFC, 2020a). “Another issue that affects the return on investment is the size of the land, the larger the land, the quicker it is” (Project Manager A)
Groundwater withdrawals	Land subsidence	+0.85	Land subsidence is one of the main challenges of largely populated area like Egypt and groundwater pumping is one of the major factors contributing to its occurrence (Aly et al., 2009). “Excessive pumping from the Nile Delta aquifer to meet the increasing demands for water could lead to aquifer system compaction and land subsidence” (Abd-Elhamid et al., 2022). Infrastructures and buildings are put in jeopardy by land subsidence, which also affects agricultural resources.
Water-Energy-Food	Water efficiency	+0.4	There are speculations stating that actors in the water, energy and food sector are interested in discussing

sectoral collaboration			water and agriculture altogether, so that water efficiency can be achieved but there are not yet proofs that shows that the collaboration had led to better policies or not (Agricultural Water Management Expert and SPIS Researcher A)
Financial aids	Installation costs	-0.85	According to the interview with project managers A and B, the financial aids provided by international organizations and Ministry of foreign affairs of allied countries supported farmers with about 70 percent of the installations cost, and financial institutions giving out loans. "Then the issue was that they're not able to afford the high upfront cost of the PV systems and the only way to support them with that would be financial support through the financial institution" (Project Manager A)
Smart irrigation	Solar pumps usage	+0.45	According to a statement by WEF Nexus Researcher and SPIS Expert B, drip irrigation is always linked with solar pumping, therefore enhancing water security and efficient use in agriculture
Smart irrigation	Water efficiency	+0.8	Among the important points mentioned by the Project Managers in Egypt is that one of the financial institutions offering financial aids are focusing on using smart irrigation methods, considering water scarcity issues and the fact that the focus areas are off-grid and desert areas. "We are asking the PV firms to also recommend the use of drip irrigation, for example, to become more water conscious" (Project Manager A). Project Manager B also confirms that water use is reduced when pumping systems are linked to modern irrigation system such as drip irrigation.

Solar Potential	Solar pumps usage	+0.55	"In general, Egypt is a good area for solar, but there are areas that are more intensely profitable to use that technology. So basically we did a geographical heat map of this area…" (Project Manager A)
Low maintenance cost	Solar pumps usage	+0.6	"…from replacing their cost of diesel as well as maintenance cost and replacement cost for the diesel powered pump because the lifetime of the solar pump is almost like as in a conservative calculation up to 20 years while the life of a diesel pump is much less up to like, five years" (Project Manager B)
Low maintenance cost	Farmer's income	+0.7	The low cost of maintenance will help farmers to save more money (IFC, 2020a). "For the farmer it's lower cost energy and accessibility to energy and more savings…so the main benefit I think in this case would be, Lower costs for the farmers and higher savings" (Project Manager A)
Energy feed-in tariff	Farmer's income	+0.65	The feeding of energy back to the grid can serve as additional source of income for the farmers regardless of the income from their agricultural produce (Agricultural Water Management Expert and SPIS Researcher A and C)
Energy feed-in tariff	Water efficiency	+0.3	The use of tariff could help farmers to conserve water and practice efficient use of water, since they can exchange excess energy for income instead of pumping more water (Agricultural Water Management Expert and SPIS Researcher A, B and C)

5.6.1. Structural analysis of FCM model

The structural analysis system indicated that the FCM consists of 27 components with 34 connections, 11 driver components, 7 receiver components and 9 ordinary components, showing the indegree, outdegree, centrality, variable type, density, connection per component and complexity score (Figure 7) (Table 9). Indegree defines the total strength of connection entering a component while outdegree defines the total strength of connection exiting a component. Centrality is the sum of indegree and outdegree. The three variables with the most significant indegree values are solar pumps usage, farmer's income and water efficiency. Also, the three variables with the most significant outdegree values are solar pumps usage, irrigation policies and low maintenance cost. The three variables with the most considerable centrality values are solar pumps usage, water efficiency and groundwater withdrawals. Solar pump usage has the highest values of indegree, outdegree and centrality which signifies that solar pump usage is the most central and most connected component in the system.

Drivers are variables affecting other concepts and cannot be controlled by other variables (i.e. zero indegree); Receivers are variables being affected by other concepts and cannot influence other variables (i.e. zero outdegree); and Ordinary components possess both non-zero indegree and outdegree. Connection per component is 1.26, which is obtained by dividing the total number of connections by the total number of components, indicating the connectedness of each node connection. The complexity score of 0.636 is obtained as the ratio of the number of receivers to the number of drivers while the density is 0.048, which is calculated by dividing the number of links by the maximum number of possible connections. The density is a clustering coefficient that indicates how well connected the whole system is.

Table 9. Structural Analysis of Concepts (Model Metrics)

Component	Indegree	Outdegree	Centrality	Type
Solar pumps usage	4.65	4.25	8.9	Ordinary
Installation costs	0.85	0.75	1.6	Ordinary
Well permits	0	0.7	0.7	Driver
End-of-life water pollution	0.45	0	0.45	Receiver
Irrigation policies	0	1.6	1.6	Driver
Diesel Pumps Usage	0.7	0	0.7	Receiver
Farmer's income	2.05	0	2.05	Receiver

Drought	0	0.8	0.8	Driver
Climate change	0.7	0	0.7	Receiver
Diesel cost	0	1.25	1.25	Driver
Rural development	0.5	0	0.5	Receiver
Water efficiency	2.5	0.7	3.2	Ordinary
Food Security	1.6	0	1.6	Receiver
Water availability	0.5	0.7	1.2	Ordinary
Ministry of water resources and irrigation	0	0.5	0.5	Driver
Energy agencies	0	0.8	0.8	Driver
Agricultural yields	0.6	0.7	1.3	Ordinary
Greenhouse gases (GHG)	0.6	0.95	1.55	Ordinary
Irrigated land	1.4	0.6	2	Ordinary
Groundwater withdrawals	1.7	0.85	2.55	Ordinary
Water-Energy-Food sectoral collaboration	0	0.4	0.4	Driver
Financial aids	0	0.85	0.85	Driver
Smart irrigation	0.8	1.25	2.05	Ordinary
Solar Potential	0	0.55	0.55	Driver
Low maintenance cost	0	1.3	1.3	Driver
Energy feed-in tariff	0	0.95	0.95	Driver
Land subsidence	0.85	0	0.85	Receiver

Total Components	27	**Number of driver components**	11
Total Connections	34	**Number of receiver components**	7
Density	0.048	**Number of ordinary components**	9
Connections per component	1.26	**Complexity Score**	0.636

HOW MIGHT SPIS BE SUCCESSFULLY ADOPTED WITHOUT OVEREXPLOITATION?

Using the system representation derived above, scenarios that show the outcomes of a couple of policy options obtained from the interviews with experts, are formed. The policy options selected were based on the most mentioned policies proposed during the interviews with experts.

5.6.2. Scenario Development

The preferred scenarios were formed from the information extracted in the interviews with experts which were then computed by the mental modeler software into a graphical representation. Figures 8, 9 and 10 present the results of the projected scenarios given an assumed combination of policy options. These scenarios shows a prediction of the extent of benefits and damages that could ensued in the presence of certain policy options or when a particular situation continues to occur.

Scenario A – This scenario was formulated based on the interviews with projects, as monitoring strategy. Project Manager A and B, in their interviews, projected the relevance and importance of well permits which is an important criteria in the selection of farmers. This is to ensure that solar pumps are not used to extract groundwater from illegal wells. WEF Nexus Researcher A and Agricultural Water Management Expert and SPIS Researcher C also emphasized the installation of drip irrigation with SPIS. In general, all the interviewees suggested the usage of smart meters. The results of the scenario in percentage increase (+) and decrease (-) are shown in figure 8. The key outcomes are 37% decrease in groundwater withdrawals, 11% increase in farmer's income, 34% increase in water efficiency, 20% increase food security, 15% decrease in greenhouse gases (GHG), 11% increase in the end-of-life water pollution.

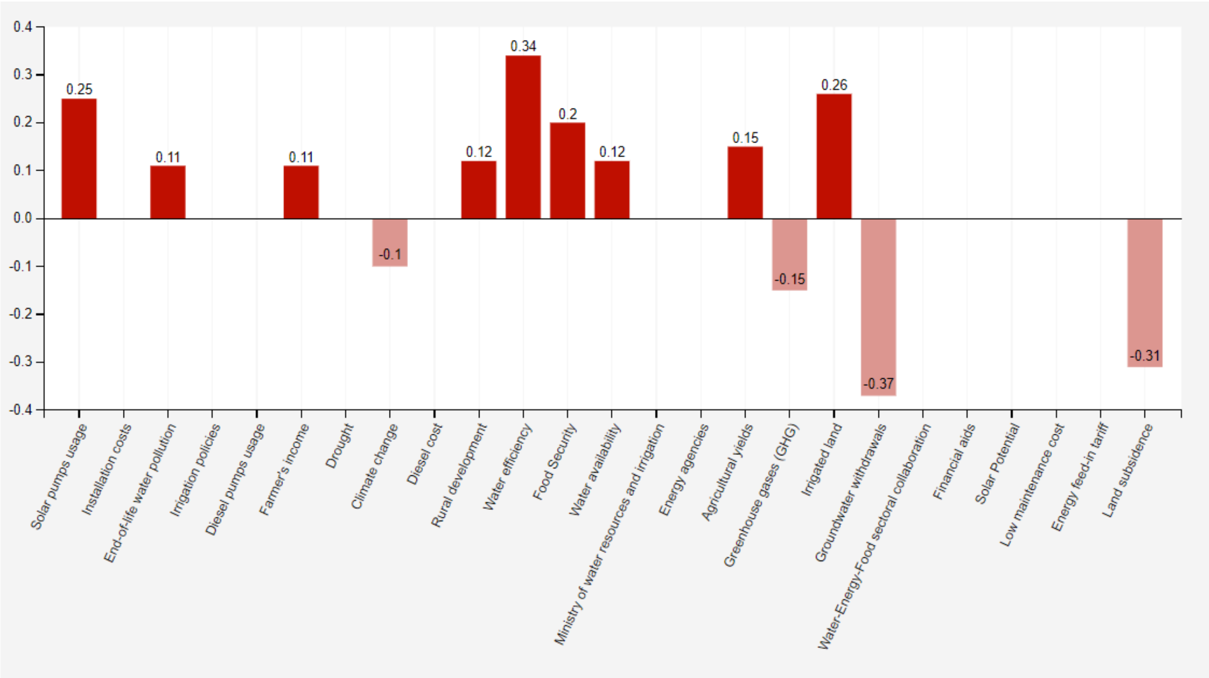


Figure 8. Scenario A – Increased well permits & increased smart irrigation

Scenario B – Interview with Project Manager A depicts poor collaboration and communication between solar firms (who are interested in the pumps, inverters and PV panels), the agriculture department (those interested in water needs of crops and crop productivity), the water resources department (those discussing about water resources) and the project implementation team. Therefore, Agricultural Water Management Expert and SPIS Researcher C suggested that establishing a relationship between the local solar companies or solar retailers and the involved farmers will do a lot of good for the sustainability of SPIS projects, especially where farmers cannot afford repair services or access spare parts, since such firms are likely to remain longer the region even after the end of the projects. According to Agricultural Water Management Expert and SPIS Researcher C, “it's important that they work much closer with the companies and don't see the companies just as a technology supplier for their project”. In addition, an interview with Agricultural Water Management Expert and SPIS Researcher A inspired the adoption of the strategy used in a project named SPaRC (Solar Power as a ‘Remunerative Crop’), in India which involved grid connected solar pumps where farmers are being paid for extra energy generated (Energy fed-in tariff) in order to control the rate of water withdrawals. All these influenced scenario B, in order to determine if the successful approach in India is applicable in Egypt. The results of the scenario in percentage increase and decrease are shown in figure 9. The key outcomes are 13% decrease in groundwater withdrawals, 34% increase in farmer’s income, 33% increase in water efficiency, 5% increase food security, 3% decrease in greenhouse gases (GHG), 3% increase in the end-of-life water pollution.

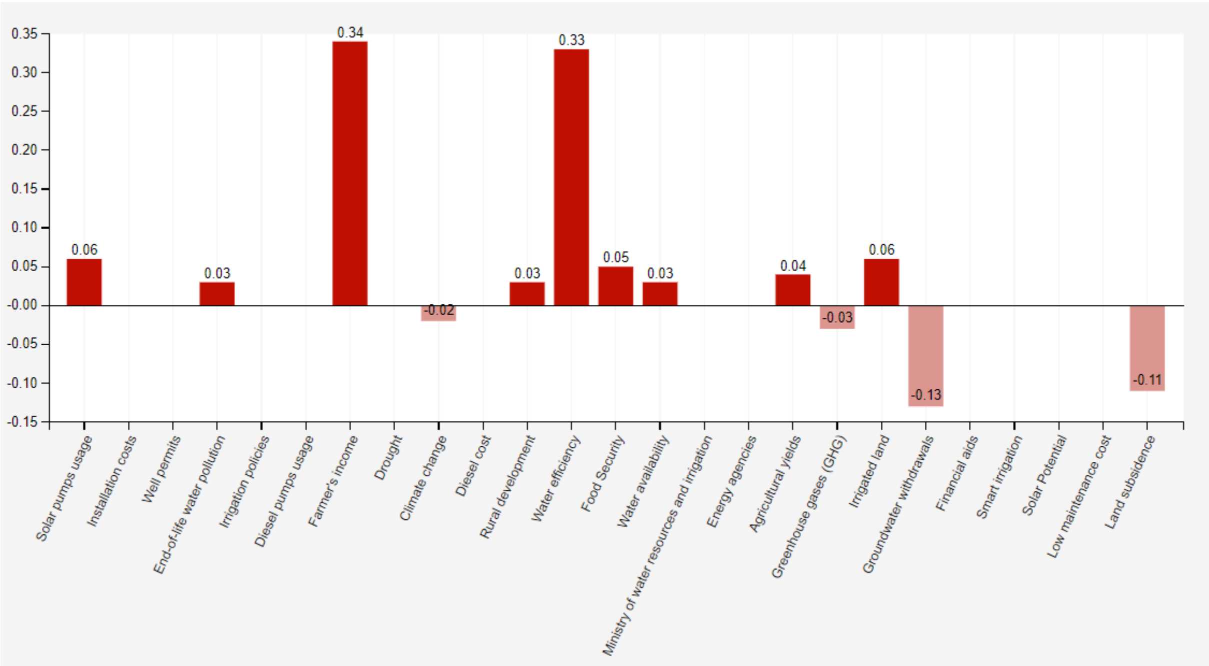


Figure 9. Scenario B - Increased energy feed-in tariff & increased Water-Energy-Food sectoral collaboration

Scenario C – Interviews with Project Managers confirms that the basic aim of SPIS projects, among others is to provide financial products (that are easily repayable) such that small scale farmers are able to purchase solar pumps, and enjoy both the environmental and economic benefits of using solar-powered pumps for irrigation. Therefore, farmers are not able to afford the capital-intensive solar-powered pumps without additional funding. All interviewees acknowledge the importance of the role of the government agencies for water resources in providing stringent irrigation policies to monitor irrigation activities in arid regions. Therefore, scenario C shows the worse situation that could occur if the above-mentioned variables are not properly supervised. The results of the scenario in percentage increase and decrease are shown in figure 10. The key outcomes are 40% increase in Installation costs, 38% decrease in smart irrigation, 54% decrease in water efficiency, 36% decrease food security, 28% increase in greenhouse gases (GHG), 19% increase in climate change.

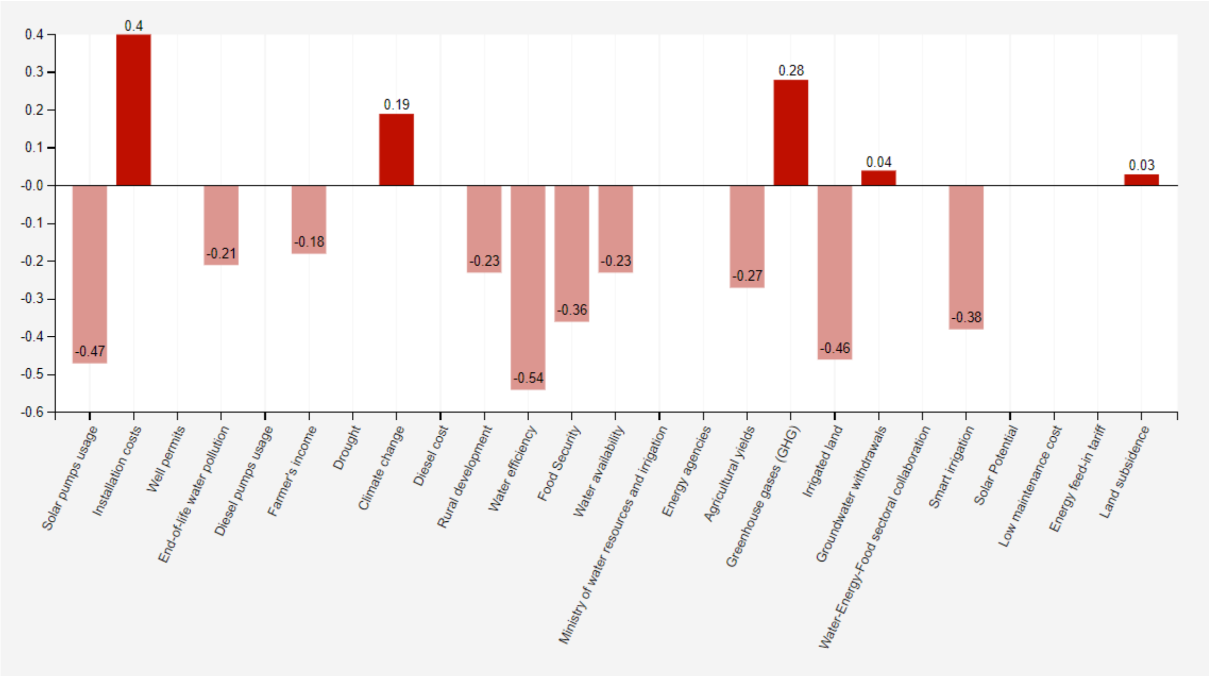


Figure 10. Scenario C - Reduced irrigation policies and reduced financial aids

The results of the scenarios and the meaning of the numbers (in percentage) are further explained in the discussion chapter.

WHAT GOVERNANCE STRATEGIES CAN BE PROPOSED TO TEMPER THE RATE OF AGRICULTURAL WATER WITHDRAWALS USING SPIS?

5.7. Proposed governance strategies

During the design process of one of the projects, farmers are being introduced to pumping cycles (for example, five hours 6 hours for only two days per week) based on the water requirements of their crops, through the coordination between the Ministry of Irrigation and Agriculture. Monitoring the amount of water withdrawn by farmers is one of the means by which overexploitation of groundwater can be curtailed. All the respondents in the interview agreed that monitoring should be enforced and it is the role of the Ministry of Agriculture and Irrigation. Suggested strategies by the Egypt-based projects and agricultural water management experts include;

- Fewer amount of large withdrawals. Farmers operating large scale agriculture should be coordinated to withdraw larger amount of water but the numbers of such farms should be kept at a minimum. This is because, in reality, large scale and mechanized farming requires large amount of water, and such kind of agriculture significantly influence the economic conditions of the country

- Energy feed-in tariffs enables the monitoring of the amount of energy generated, it therefore serves as a proxy to monitor water withdrawals. Solar Pumps that are connected to the grid such that energy used and generated can be monitored and by implication, the amount of water withdrawn
- Mandating the coupling of drip irrigation or any other form of smart irrigation systems with solar pump irrigation installations
- Installation of flow meters to measure flowrates and determine the amount of water moving through a pipe of the solar pump systems
- Encouraging agriculture in wetter part of the countries e.g. Nile valley and Delta
- Incentives for crops with lesser water requirements by the Ministry of Agriculture and this could minimize the cultivation of water-intensive crops among the farmers that depends on groundwater for irrigation

DISCUSSION

WHAT ARE THE WATER RESOURCES AVAILABLE AND THE ENVIRONMENTAL REGULATORY IN PLACE, AND HOW DO THEY INFLUENCE THE ADOPTION OF SPIS?

According to the results above, about 80 percent of water consumption in Egypt is attributed to agriculture and irrigation activities which differs from the general notion that domestic and industrial uses are the major usage of water. Over the years, Egypt as had a major control of the Nile resources, almost 90%, because of the colonial-era treaty. Recently, neighbouring countries like Ethiopia is taking advantage as an upstream country to gain more dominance over the Nile with the construction of the great Ethiopian renaissance dam GERD for hydropower generation. The major issue posed is the Egyptians' concerns over the decrease in the allocated share of the Nile. Since the concerned countries, Sudan and Egypt, related their disagreement, there had been the occurrences of water conflicts.

The initial abundance of the Nile water has encouraged the use of flood irrigation in agriculture and this behaviour towards water use might be difficult to change in reality. However, as population increased and the volume of water flowing into the Nile reduced, there are campaigns aimed at rationalizing water utilization. "As Egypt has already been experiencing a sharp decline of renewable freshwater per capita (from 900 cubic meters in 2000 to 600 cubic meters in 2017), it is expected that the effect of the GERD - in addition to climate change impacts - would only exacerbate the water issue in Egypt, edging the country closer to severe water scarcity of 500 cubic meters per capita in the future" (Gad, 2017). All these above factors, along with the effects of climate change on water resources, could increase Egypt's reliance on groundwater resources, especially during the dry months.

Desalination is another option to provide water for irrigation purposes and it could be lucrative for Egypt who has abundant solar potential as source of energy and seawater. The process is energy intensive and very expensive even though the energy source is renewable. As the Middle East and North Africa (MENA) region is expected to experience incessant heatwaves, it is smarter to also intentionally direct policies towards water conservation technologies to preserve the natural underground water reserves.

The actual agricultural land in Egypt is limited. Land fragmentation in policy has the potential to reduce the sustainable use of agricultural land and water resources. In the Sustainable

Agricultural Development Strategy (SADS) 2030, no regulation protects arable land from fragmentation, instead land extension is being encouraged (Tellioglu & Konandreas, 2017). According to the interview with one of the project coordinators, it was stated that one of the factors considered during the selection of farmers is the size of the farmland. For profitability when using solar pumps, farmers with less than one feddan of lands are not considered. In Egypt, reclaimed lands are easily converted for residential or tourism purposes, such that the aim of land reclamation, that is, agricultural development, is neglected. However, land reclamation policies can promote the use of solar pump irrigation on a larger scale in desert areas. Water policies encouraging the exploitation of deep groundwater resources are some of the policies boosting the adoption of solar pump irrigation for groundwater withdrawal. The issue with this is the determination of depth which is deep enough for safe groundwater abstraction and also deeper depths means increased costs.

Generally, solar pump irrigation system is introduced in order to contribute to the transition to renewables, achieving climate-smart agriculture (CSA) and reduction of GHG emissions. Therefore, the shift of farmers towards solar pump irrigation is included in the National Determined Contributions (NDC) of Egypt towards climate change mitigation.

WHAT ARE THE EFFECTS OF SOLAR PUMPING ON WATER, FOOD AND ENERGY RESOURCES?

The adoption of solar pump irrigation tends to increase groundwater abstraction because it involves the use of "free energy". Since the extraction of water is not monitored, it can be used for both irrigation or for other purposes, and it potentially increase the amount of irrigated land and food production. Solar pump irrigation systems projects are usually directed at remote areas and desert areas in North Africa. The solar irrigation system is very capital intensive even though most of the initial cost is bore by financial aids from government. On the other hand, water extracted and energy should be utilized to their full capacity. Therefore, it is essential that the energy produced by the PV panels own by farmers is not wasted in anyway.

In some of the projects, solar pumps are designed based on the water requirement of the farm. During the design of SPIS projects, consultants take the optimal water requirements of crops cultivated on the farm into consideration in order to determine the size of PV pumps for specific farms. These requirements are usually published by the Ministry of Agriculture and Irrigation.

This kind of approach is essential to ensure that energy use and water use is optimal for food production.

SPIS irrigation improves food production and retrieves groundwater resources using a sustainable energy source, such that, regional government is focusing on the improvement of irrigation systems. Yet, both the activation of conventional rainwater collection systems and the development of rain-fed agriculture are of similar significance, as many regions lack accessible and renewable groundwater supplies. When promoting solar-powered pumps, food security, the use of renewable energy, and the sustainability of groundwater resources should be considered in every instance.

HOW CAN THE IN-FIELD CONTEXT BE REPRESENTED IN A SYSTEMATIC WAY TO MODEL POLICY SCENARIOS?

Researches on the system representation of WEF nexus have thus far used the following modeling tool: NexSym, $IM_{3,}$ WEF nexus tool 2.0, WEAP, ECHO, COFFEE, IMAGE. In this research, I used fuzzy cognitive mapping to set up a simple model and found that it is also quite effective. The use of the fuzzy cognitive mapping displayed a system representation of different aspects of SPIS projects, its design and adoption, such that the circumstances and policy scenarios are easily computed numerically.

HOW MIGHT SPIS BE SUCCESSFULLY ADOPTED WITHOUT OVEREXPLOITATION?

Having the highest centrality value, solar pump usage is both mainly affected by other components and mainly influencing other components in the system. The outputs of scenario A (**Increased well permits & increased smart Irrigation)** and scenario B (**Increased Energy feed-in tariff & increased Water-Energy-Food sectoral collaboration)** are presented in Table 10. Both scenarios show the same characteristics but with different quantity. A exhibits 37% decrease in groundwater withdrawal while B is 13%. This shows that the policy options combination in A has the highest probability to minimize withdrawals and also improve food security better than B. Smart irrigation will help conserve water and avail more water for cultivation. However, B projects the highest income (34%) for farmer, taking cognisance of the importance of livelihood for farmers.

According to the interview with Agricultural Water Management Expert and SPIS Researcher A, Farmers tend to cooperate with policies that will improve their savings and income, especially the rural dwellers which is evident in the Indian project that involved energy feed-in tariffs. Both scenarios projected almost the same level of water efficiency. Scenario A also show better decline in greenhouse gas emission and climate change, which is one of the main reasons why solar pump irrigation was introduced. Rural development and agricultural yield increase more in scenario A than in B. However, the end of life pollution of A is higher than B because A encourages more adoption of solar pump irrigation system, hence, PV panel waste to deal with in future. Both scenarios have their strength and weaknesses, but scenario B shows a good balance if farmer's income and end of life pollution are considered, even though the reduction in groundwater withdrawal is more favourable in A. Nonetheless, combining all the four policy options gave valuable results in the design and implementation of solar pumps projects (Table 10). The key outcomes are 46% decrease in groundwater withdrawals, 42% increase in farmer's income, 60% increase in water efficiency, 23% increase food security, 17% decrease in greenhouse gases (GHG) 15% increase in the end-of-life water pollution. The graphical representation of this 'new' scenario is presented in Appendix D.

Table 10. Positive scenarios A and B evaluation

Concepts			**Percentage Change**		
			Scenario A	**Scenario B**	**All four policy options**
Main outcomes	Groundwater withdrawals	↓	37%	13%	46%
	Farmer's income	↑	11%	34%	42%
	Water efficiency	↑	34%	33%	60%
	Food security	↑	20%	5%	23%
	Greenhouse gases (GHG)	↓	15%	3%	17%
Additional outcomes	Solar pumps usage	↑	25%	6%	29%
	Land Subsidence	↓	31%	11%	38%
	Rural development	↑	12%	3%	15%

	Climate change	↓	10%	2%	12%
	Water Availability	↑	12%	3%	15%
	Agricultural yields	↑	15%	4%	18%
	Irrigated land	↑	26%	6%	30%
Consequences	End-of-life water pollution	↑	11%	3%	13%

Note: ↑ means Increase and ↓ means decrease

Scenario C **(Reduced irrigation policies and reduced financial aids)** (Table 11) is the negative scenario that projected a 40% increase installation costs of solar pumps since financial aids are being reduced and small scale farmers won't be able to afford the technology, therefore solar pump usage reduces. Water efficiency and smart irrigation reduced because the adoption of solar pump irrigation created more shift towards smart irrigation systems, and groundwater withdrawals increased due to lesser irrigation policies. Therefore, withdrawals can still continue even with the use of the old diesel pumps which led to a 28% increase in greenhouse gases emission. Food security, irrigated land and agricultural yield decreased since the supposed water availability decreased also. Climate change increased as well, since greenhouse gases emission hiked. Endeavours to reduce the use of solar pump irrigation systems have its own repercussions, therefore, this technology has come to stay.

Table 11. Negative scenario C evaluation

Concepts			**Percentage Change**
Main outcomes	Installation costs	↑	40%
	Groundwater withdrawals	↑	4%
	Smart irrigation	↓	38%
	Water efficiency	↓	54%
	Food security	↓	36%
	Greenhouse gases (GHG)	↑	28%

Additional outcomes	Solar pumps usage	↓	47%
	Rural development	↓	23%
	Water Availability	↓	23%
	Agricultural yields	↓	27%
	Irrigated land	↓	46%
	Farmer's income	↓	18%
	End-of-life water pollution	↓	21%
Consequences	Land Subsidence	↑	3%
	Climate change	↑	19%

Note: ↑ means Increase and ↓ means decrease

6.1. Relation with WEF nexus interlinkages (Causal loop diagrams)

The water-food causal loop (Figure 11) presents the water-for-food relationship from the mind map in figure 7, as water being pumped to irrigate more land and produce more foods. Therefore irrigation policies in the form of smart irrigation ensures the efficient use of water on agricultural land and reclaimed land. Such policies can also discourage the use of solar pumps for flood irrigation. The energy-for-food causal loop (Figure 12) shows the influence of high solar potential on the shift towards the adoption solar pumps, resulting to more agricultural yield and turning 'energy into food'. Energy feed-in tariff can aid to channel this high solar potential into more income for the farmers. The energy-for-water causal loop diagram (Figure 13) describes the utilization of abundant energy and high diesel cost to drive the promotion of solar pumps for water withdrawals. Energy feed-in tariff and well permits could curb the rate of groundwater withdrawals. All these aforementioned policies can determine the systemic change and the weight of effects of these causal loop in the mind map.

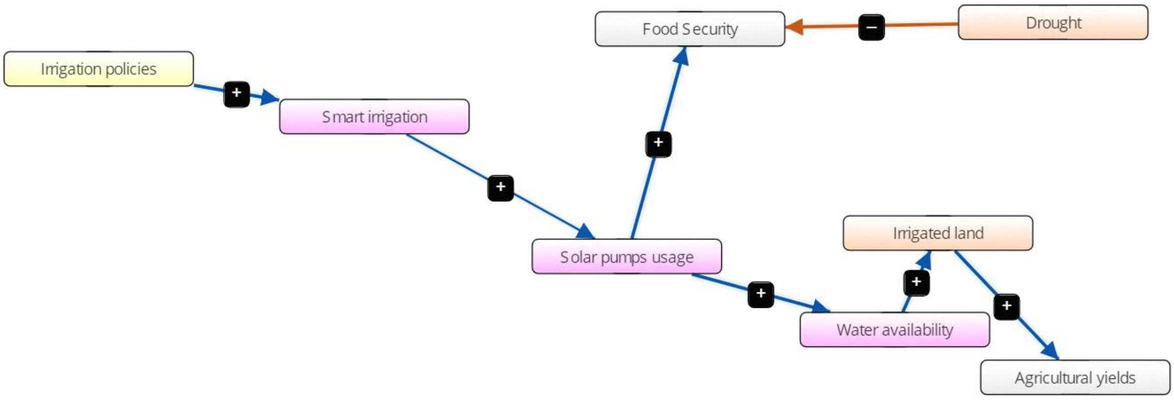


Figure 11. "Water for food" causal loop

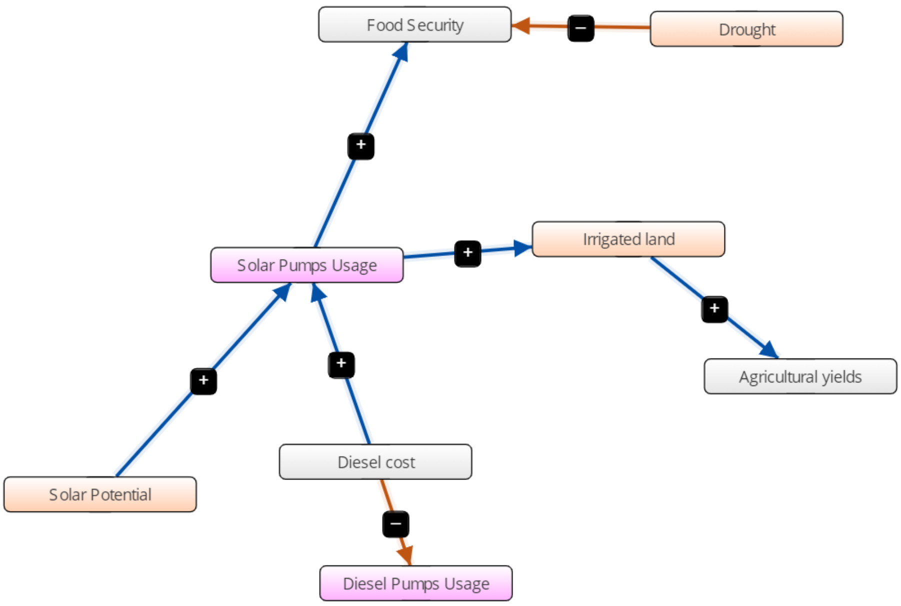


Figure 12. "Energy for food" causal loop

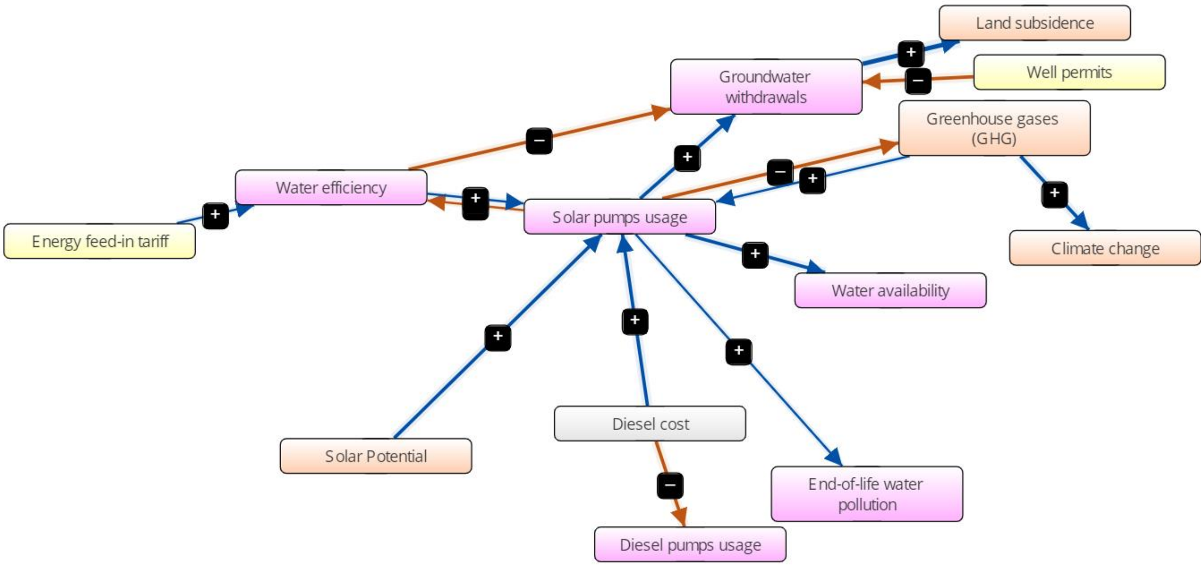


Figure 13. "Energy for water" causal loop

According to interviews with Agricultural Water Management Expert and SPIS Researcher A and Project Manager A, the adoption of solar pump irrigation systems is spreading rapidly and farmers are relatively enthusiastic to adopt this technology. Groundwater plays a very important role as buffer against drought in higher temperature region and should be protected. Otherwise, the vulnerability of farmers to climate change especially in drier regions will worsen significantly since reduced groundwater levels increases the effects of drought. However, if solar pumps are promoted such that famers can still make profits or sustain their livelihood even during drought, then groundwater can be protected. Energy feed-in tariff as a policy instrument can achieve this, such that farmers can sell energy generated to the government.

Consequently, as the adoption of solar pump is of a greater cause towards the shift to climate smart agriculture, new challenges arises as the usage intensifies in arid regions. Therefore, combinations of several policy instruments are essential from the design stage of solar pump irrigation projects, up until the consuming stage, as well as the involvement of relevant stakeholders at all stages of the projects.

WHAT GOVERNANCE STRATEGIES CAN BE PROPOSED TO TEMPER THE RATE OF AGRICULTURAL WATER WITHDRAWALS USING SPIS?

In the discussions with Solar pump irrigation project design and implementation team, it was inferred that despite consultations with ministry of water resource and irrigation, most projects have little or no contributions from them. In addition, government agencies of energy resources and solar energy firms tend to have more control over such projects and the participants. This shows the weak link of coordination among actors in water, food and energy sectors. While solar pump irrigation is good for the energy and food sector, the water sector can only continue to develop better ways to ensure that water withdrawal is kept at a minimum.

Monitoring the amount of water withdrawn by farmers could be very expensive especially if people are being employed to do so. In Egypt, a national monitoring program that monitors water pollution in the main stream channels of the Nile river was carried out in 2018, in which smart monitoring devices called “YSI sondes” were installed in about 20 monitoring station along the river and data are collected using cellular GPRS modems every 30 minutes (Gabr, 2020; WaterWorld, 2018). The sondes measure broad ranges of water quality parameters and real time data is sent to the Ministry of Environment (WaterWorld, 2018). Such smart monitoring could also be employed for groundwater monitoring. According to WaterWorld (2018), smart monitoring devices that uses cellular modems as are less costly than satellite.

As governmental bodies of Agriculture can also offer incentives to farmers for using less water-intensive practices, they should also be sensitized to the environmental benefits of water conservation and the economic value of less water-intensive crops. In addition, large number of farmers withdrawing in smaller amounts can be costly and difficult to monitor unlike few farmers withdrawing in large amounts. Enforcement of the installation of smart irrigation systems such as drip and sprinkler irrigation systems with solar pump irrigation system (SPIS) and this should be mandated for any solar pump related projects involving any form of water resource.

A pilot project in India, SPaRC (Solar Power as a ‘Remunerative Crop’), which involved grid connected solar pumps is the world’s first solar irrigation cooperative aced by the International Water Management Institute (IWMI) (IWMI, 2016; Shah et al., 2016). This was successfully carried out in a village, and then the government of Gujarat (Western India) introduced another project that installed about 4500 solar pumps (“with a total capacity of 106.47 MW and a Feed in tariff set at Rs. 3.5 per kW”) which are connected to the feeder (India Water Portal, 2022).

However, an interview with Agricultural Water Management Expert and SPIS Researcher A reveals that researches are ongoing to understand the experiences of the farmers. Farmers are being monitored based on the amount of energy generated and they are being paid according to the differences between energy generated and energy used for pumping water. That way, “Solar irrigation pumps… can be a composite Energy-Water-Livelihoods-Carbon solution rather than just 'green' pumping tools” (Verma et al., 2016). This strategy as a pilot project can also be adopted in regions where over-exploitation or over dependency on groundwater is high in Egypt.

CONCLUSIONS AND RECOMMENDATIONS

Experts on irrigation in arid climates believe that at a particular point, choices have to be made between two pump-types, one operated by fossil fuels or the other by solar energy. Based on the observation from solar projects, results of this study, investments should be channelled towards increasing the efficiency of solar pumps, and regional government should continue to designed schemes and initiatives to educate farmers and encourage them to pump water reasonably. There are speculations that farmers just wants to earn more money since they depend on agriculture for livelihood, therefore it will be smart for policy makers to include strategies that will improve the savings of farmers, particularly in areas where groundwater depletion is inevitable. Areas with aquifers that are not rechargeable should be given special attention. If groundwater abstraction continues and water levels keep decreasing, inhabitants might experience environmental crisis in future which might force them to migrate out of their homes, putting more pressure on the population density and resources of other locations where they will move to. Such displacement can negatively influence the economic stability of a country.

Most of the respondents during the interview confirms that pumping of more water by farmers does not guarantee that they can produce more food. Instead, there is higher tendency that farmers can become more wasteful. Observations in this study include the fact that project design focus are centred around market study, financing and energy transition. It is suggested that the same effort should be directed at considering and obtaining data related to geographical groundwater levels, available groundwater resources and rechargeable aquifers. This could help project implementers select regions where large adoption of solar pump irrigation system is viable and also contribute to sustainable withdrawals of groundwater.

In this study, the importance of the collaboration between food, water and energy sectors is presented. However, one of the challenges being experience during the design of solar pumps irrigation projects is the communication issues between solar firms (who are interested in the pumps, inverters and PV panels), the agriculture department (those interested in water needs of crops and crop productivity) and the water resources department (those discussing about water resources). For a successful project implementation, there is need to speak a common ‘language’ while considering the perspective of each group. Therefore, joint workshops and trainings among these different groups can improve their communication and collaboration.

50% of the interviewees mentioned water security as the priority when considering the promotion of water-related technology like solar pump irrigation in semi-arid regions because those areas are already battling water scarcity and are consistently looking for new water resources such as desalination. While others focus on the effects of greenhouse gases on the environment, as solar pumping is one of the strategies to reduce agriculture's contribution to climate change. And moreover, climate change negatively affects water resources. Nevertheless, all the respondents agreed that solar pumping should continue to be promoted among farmers while we continue to develop policies and monitoring schemes in form of information/awareness and incentives to support the sustainable withdrawal of water. As demonstrated in India, government should establish schemes that create opportunities for farmers to sell excess energy from the PV system to the grid since governments can buy electricity from energy companies. This kind of synergy can benefit both farmer's livelihood and energy security in rural areas.

Solar pump irrigation systems projects are increasing year in, year out and are being included in future plans to reduce greenhouse gases. In addition, the use of solar pumps began about 10-15 years ago and some PV panels were installed, which means that in few years times, old panels will be abandoned. Therefore, there is the urgency to develop strategies for the disposal of solar PV panels. Hence, separate and several sets of policies should be specifically designed for solar pumps addressing financing, awareness, trainings, monitoring, evaluation of farmers performance and disposal of PV cells. Beyond energy transition and reduction of green-house gases, sustainability factors such as prospective underground water withdrawals, amount of water available and accessible should be considered and investigated before the approval or conceptualization of any SPIS project.

Local technicians should be trained to understand and operate the solar pumps irrigation and should be allowed to join the installation team of projects in order to familiarize themselves with the system. This could contribute to the rural development aspect of solar pumps and the maintenance of the irrigation system to reach up to its 20-year life span. Another recommendation is that financial aids for the purchase of solar pump irrigation system should be targeted. In addition, Further monitoring of projects by financing institutions and the engagement of related stakeholders (e.g. NGOs) can buttress the accountability of project implementers. Integrated policies approach coupled with incentives, tariffs, permits and techno-regulations can improve the sustainable implementation of the project and adoption of solar pump irrigation systems (SPIS) while protecting groundwater reserves.

Certainly, one of the biggest problems to feeding an ever-growing society while supporting an already pressured ecosystem is the effects of climate change on water availability for agricultural activities in dry places (Abdelfattah, 2021). The fundamental conclusion of this study is that solar-powered pump irrigation systems need continuous regulation improvement and management revision together with other improvised groundwater abstraction methods, particularly in agriculture but also for household, industrial and other purposes. This is important for the sustainable management of Egypt's limited freshwater supplies. The primary findings of the system-represented projection is that, without the presence of well implemented policies, the continuous adoption of solar energy for irrigation in sun-rich and renewable groundwater-scarce Egypt is projected to negatively impact groundwater supplies. In addition, the most important factor influencing the appeal of SPIS to farmers has been the low marginal cost of solar pump irrigation after the first expenditure. Therefore, SPIS is another system that, if not properly controlled, might exacerbate overall water shortage of arid regions.

REFERENCES

Abdalla, A. A., & Abdel Nour, H. O. (2001). The Agricultural Potential of Sudan. *Executive Intelligence Review (EIR) , 28*(8). https://larouchepub.com/eiw/public/2001/eirv28n08-20010223/eirv28n08-20010223_037-the_agricultural_potential_of_su.pdf

Abdelfattah, M. A. (2021). Climate Change Impact on Water Resources and Food Security in Egypt and Possible Adaptive Measures. *Emerging Challenges to Food Production and Security in Asia, Middle East, and Africa*, 267–291. https://doi.org/10.1007/978-3-030-72987-5_10

AbdelGadir, E. K., & Hammad, M. A. (2014). *Technical and Economical Feasibility of Solar PV Pumping of Water in Sudan*.

Abd-Elhamid, H. F., Abd-Elkader, B. S., Wahed, O., Zeleňáková, M., & Abd-Elaty, I. (2022). Assessment of Changing the Abstraction and Recharge Rates on the Land Subsidence in the Nile Delta, Egypt. *Water 2022, Vol. 14, Page 1096, 14*(7), 1096. https://doi.org/10.3390/W14071096

Abd Ellah, R. G. (2020). Water resources in Egypt and their challenges, Lake Nasser case study. *The Egyptian Journal of Aquatic Research*, *46*(1), 1–12. https://doi.org/10.1016/J.EJAR.2020.03.001

Abdel-Shafy, H. I., El-Saharty, A. A., Regelsberger, M., & Platzer, C. (2010). Rainwater in Egypt: Quantity, distribution and harvesting. *Mediterranean Marine Science*, *11*(2), 245–257. https://doi.org/10.12681/MMS.75

Abdin, A. E., Afify, A., & Adel, A. (2011). Comparative analysis of Egyptian Water Policy and Water Framework Directive. In S. Junier, M. el Moujabber, G. Trisorio-Liuzzi, S. Tigrek, M. Serneguet, R. Choukr-Allah, M. Shatanawi, & Rodríguez R. (Eds.), *Dialogues on Mediterranean water challenges: Rational water use, water price versus value and lessons learned from the European Water Framework Directive.* (pp. 169–179). Centre International de Hautes études agronomiques méditerranéennes (CIHEAM).

Abdin, A. E., & Gafaar, I. (2009). Egyptian Water Policies towards Increasing its Value . In *MELIA workshop* (Vol. 2123). https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Egyptian+Water+Policies+towards+Increasing+its+Value&btnG=#d=gs_cit&t=1656406607837&u=%2Fscholar%3Fq%3Dinfo%3ArtZ-fq_IxPUJ%3Ascholar.google.com%2F%26output%3Dcite%26scirp%3D0%26hl%3Den

Abdou, D., & Ibrahim, A. A. (2019). Solar Water Pumps: The Case of Egypt's Desert. In *Egypt Network for Integrated Development (ENID/EL NIDAA).* https://elnidaa.org/app/uploads/2019/07/CS13_solar_water_pumps.pdf

Abdourraziq, S., Abdourraziq, M. A., & Darab, C. (2017). Photovoltaic water pumping system application in Morocco. *2017 11th International Conference on Electromechanical and Power Systems, SIELMEN 2017 - Proceedings, 2017-January*, 271–274. https://doi.org/10.1109/SIELMEN.2017.8123331

Abu-aligah, M. (2011). Design of photovoltaic water pumping system and compare it with diesel powered pump. *Jordan Journal of Mechanical and Industrial Engineering , 5*, 273–280. https://www.researchgate.net/publication/285839824_Design_of_photovoltaic_water_pumping_system_and_compare_it_with_diesel_powered_pump

AbuZeid, K. M. (2020). Existing and recommended water policies in Egypt. *Global Issues in Water Policy*, *23*, 47–62. https://doi.org/10.1007/978-3-030-29274-4_3/FIGURES/6

Adghough, J. (2018). Economic Overview of Agriculture and Food in Morocco. *Cuvillier Verlag, Inhaberin Annette Jentzsch-Cuvillier*. https://cuvillier.de

Aeschbach-Hertig, W., & Gleeson, T. (2012). Regional strategies for the accelerating global problem of groundwater depletion. *Nature Geoscience 2012 5:12*, *5*(12), 853–861. https://doi.org/10.1038/ngeo1617

AFDB. (2021, February). *Sudan - Solar PV Powered Pumping for Irrigation Project (Desert-to-Power Initiative) - Project Appraisal Report | African Development Bank - Building today, a better Africa tomorrow*. African Development Bank Group. https://www.afdb.org/en/documents/sudan-solar-pv-powered-pumping-irrigation-project-desert-power-initiative-project-appraisal-report

Aklan, M. M., & Lackner, H. (2021). Solar-Powered Irrigation In Yemen: opportunities, challenges And policies. *The Sana'a Center for Strategic Studies*. https://doi.org/10.1016/S0140-6736(16)00389-5

Ali, B. (2018). Comparative assessment of the feasibility for solar irrigation pumps in Sudan. *Renewable and Sustainable Energy Reviews*, *81*, 413–420. https://doi.org/10.1016/J.RSER.2017.08.008

Allouche, J., Middleton, C., & Gyawali, D. (2015). Technical Veil, Hidden Politics: Interrogating the Power Linkages behind the Nexus. *Water Alternatives*, *8*(1), 610–626. www.water-alternatives.org

Al-Smairan, M. (2012). Application of photovoltaic array for pumping water as an alternative to diesel engines in Jordan Badia, Tall Hassan station: Case study. *Renewable and Sustainable Energy Reviews*, *16*(7), 4500–4507. https://doi.org/10.1016/J.RSER.2012.04.033

Aly, M. H., Zebker, H. A., Giardino, J. R., & Klein, A. G. (2009). Permanent Scatterer investigation of land subsidence in Greater Cairo, Egypt. *Geophysical Journal International*, *178*(3), 1238–1245. https://doi.org/10.1111/J.1365-246X.2009.04250.X/2/178-3-1238-FIG005.JPEG

Armanuos, A. M., Negm, A., & Tahan, A. H. M. H. el. (2016). Life Cycle Assessment of Diesel Fuel and Solar Pumps in Operation Stage for Rice Cultivation in Tanta, Nile Delta, Egypt. *Procedia Technology*, *22*, 478–485. https://doi.org/10.1016/J.PROTCY.2016.01.095

Asgharnejad, H., Khorshidi Nazloo, E., Madani Larijani, M., Hajinajaf, N., & Rashidi, H. (2021). Comprehensive review of water management and wastewater treatment in food processing industries in the framework of water-food-environment nexus.

Comprehensive Reviews in Food Science and Food Safety, *20*(5), 4779–4815. https://doi.org/10.1111/1541-4337.12782

Baconi, T. (2018, November 13). *Testing the water: How water scarcity could destabilise the Middle East and North Africa* . European Council on Foreign Relations (ECFR). https://ecfr.eu/publication/how_water_scarcity_could_destabilise_the_middle_east_and_north_africa/

Bardi, U., el Asmar, T., & Lavacchi, A. (2013). Turning electricity into food: the role of renewable energy in the future of agriculture. *Journal of Cleaner Production*, *53*, 224–231. https://doi.org/10.1016/J.JCLEPRO.2013.04.014

Barton, A. (2022). *Water In Crisis - Spotlight Sudan*. The Water Project. https://thewaterproject.org/water-crisis/water-in-crisis-sudan

Basheer, A. (2008, December). *Prospects of Sustainable Utilization of Sudan Water Resources in Agriculture*. https://www.researchgate.net/publication/301327653_PROSPECTS_OF_SUSTAINABLE_UTILIZATION_OF_SUDAN_WATER_RESOURCES_IN_AGRICULTURE

Bassi, N. (2015). Irrigation and Energy Nexus: Solar Pumps Are Not Viable. *Economic and Political Weekly*, *50*(10), 63–66. http://www.jstor.org/stable/24481458

Bastakoti, R., Raut, M., & Thapa, B. R. (2020). *Groundwater Governance and Adoption of Solar-Powered Irrigation Pumps*. https://doi.org/10.1596/33245

Bazzi, S., & Blattman, C. (2014). Economic Shocks and Conflict: Evidence from Commodity Prices. *American Economic Journal: Macroeconomics*, *6*(4), 1–38. https://doi.org/10.1257/MAC.6.4.1

Benson, D., Gain, A. K., & Rouillard, J. J. (2015). Water Governance in a Comparative Perspective: From IWRM to a "Nexus" Approach? *Water Alternatives*, *8*(1), 756–773. www.water-alternatives.org

Bieber, N., Ker, J. H., Wang, X., Triantafyllidis, C., van Dam, K. H., Koppelaar, R. H. E. M., & Shah, N. (2018). Sustainable planning of the energy-water-food nexus using decision making tools. *Energy Policy*, *113*, 584–607. https://doi.org/10.1016/J.ENPOL.2017.11.037

Boelee, E., & Laamrani, H. (2004). Multiple use of irrigation water in Northeastern Morocco. In P. Moriarty, J. Butterworth, & B. van Koppen (Eds.), *Beyond Domestic: Case studies on poverty and productive uses of water at the household level* . IRC International Water and Sanitation Centre. (Technical Paper Series; no. 41).

Bogardi, J. J., Dudgeon, D., Lawford, R., Flinkerbusch, E., Meyn, A., Pahl-Wostl, C., Vielhauer, K., & Vörösmarty, C. (2012). Water security for a planet under pressure: Interconnected challenges of a changing world call for sustainable solutions. *Current Opinion in Environmental Sustainability*, *4*(1), 35–43. https://doi.org/10.1016/J.COSUST.2011.12.002

Bouchaou, L., Tagma, T., Boutaleb, S., Hssaisoune, M., & el Morjani, Z. E. A. (2011). Climate change and its impacts on grounwater resources in Morocco: the case of the

Souss-Massa basin. In H. Treidel, J. L. Martin-Bordes, & J. Gurdak (Eds.), *Climate Change Effects on Groundwater Resources: A Global Synthesis of findings and recommendations* (p. 129). CRC Press. https://books.google.nl/books?hl=en&lr=&id=6QbNBQAAQBAJ&oi=fnd&pg=PA129&dq=morocco+Current+water+needs+increasingly+exceed+the+available+renewable+resources,+particularly+as+a+result+of+demographic+pressure&ots=WFNuE5PQ9X&sig=wGvrldqqalljAs5t5Z4b364v5IY&redir_esc=y#v=onepage&q=morocco%20Current%20water%20needs%20increasingly%20exceed%20the%20available%20renewable%20resources%2C%20particularly%20as%20a%20result%20of%20demographic%20pressure&f=false

Brunet, C., Savadogo, O., Baptiste, P., & Bouchard, M. A. (2018). Shedding some light on photovoltaic solar energy in Africa – A literature review. *Renewable and Sustainable Energy Reviews*, *96*, 325–342. https://doi.org/10.1016/J.RSER.2018.08.004

Burney, J., Woltering, L., Burke, M., Naylor, R., & Pasternak, D. (2010). Solar-powered drip irrigation enhances food security in the Sudano-Sahel. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(5), 1848–1853. https://doi.org/10.1073/PNAS.0909678107/SUPPL_FILE/PNAS.0909678107_SI.PDF

CAPMAS. (2016). *Egypt in figures*. Central Agency for Public Mobilization and Statistics (CAPMAS). https://www.capmas.gov.eg/Pages/StaticPages.aspx?page_id=5035

Carr, J. A., D'Odorico, P., Laio, F., & Ridolfi, L. (2013). Recent History and Geography of Virtual Water Trade. *PLOS ONE*, *8*(2), e55825. https://doi.org/10.1371/JOURNAL.PONE.0055825

Chandel, S. S., Nagaraju Naik, M., & Chandel, R. (2015). Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies. *Renewable and Sustainable Energy Reviews*, *49*, 1084–1099. https://doi.org/10.1016/J.RSER.2015.04.083

Chirisa, I., Mutambisi, T., Chivenge, M., Mabaso, E., Matamanda, A. R., & Ncube, R. (2020). The urban penalty of COVID-19 lockdowns across the globe: manifestations and lessons for Anglophone sub-Saharan Africa. *GeoJournal 2020 87:2*, *87*(2), 815–828. https://doi.org/10.1007/S10708-020-10281-6

Cook, C., & Bakker, K. (2012). Water security: Debating an emerging paradigm. *Global Environmental Change*, *22*(1), 94–102. https://doi.org/10.1016/J.GLOENVCHA.2011.10.011

Dadhich, G., & Shrivastava, V. (2018). Economic comparison of solar PV and diesel water pumping system. *IEEE International Conference on Information, Communication, Instrumentation and Control, ICICIC 2017*, 1–6. https://doi.org/10.1109/ICOMICON.2017.8279156

Dahchour, A., & el Hajjaji, S. (2019). Water resources in morocco as impacted by climate change. In A. Al-Omari & M. E. Aydin (Eds.), *Water Perspectives in Emerging Countries Water Resources and Climate Change: Impacts, Mitigation and Adaptation*. https://cuvillier.de/de/shop/publications/8140

Daher, B. T., & Mohtar, R. H. (2015). Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. *Https://Doi.Org/10.1080/02508060.2015.1074148*, *40*(5–6), 748–771. https://doi.org/10.1080/02508060.2015.1074148

Danish, M. S. S., Senjyu, T., Sabory, N. R., Khosravy, M., Grilli, M. L., Mikhaylov, A., & Majidi, H. (2021). A Forefront Framework for Sustainable Aquaponics Modeling and Design. *Sustainability 2021, Vol. 13, Page 9313*, *13*(16), 9313. https://doi.org/10.3390/SU13169313

Devaux, P. (2019). *Egypt: The challenges of the agricultural sector | Economic Research-BNPParibas*. BNP Paribas: 2nd Quarter Economic Research . https://economic-research.bnpparibas.com/html/en-US/challenges-agricultural-sector-4/19/2019,32926

Diaco, M., Alami Merrouni, M., & Bougarrani, S. (2020). Circular economy in the Africa-EU cooperation - Country report for Morocco. *Country Report under EC Contract ENV.F.2./ETU/2018/004 Project: " "Circular Economy in Africa-Eu Cooperation", Trinomics B.V., ACEN, Adelphi Consult GmbH and Cambridge Econometrics Ltd*. https://doi.org/10.2779/211421

D'Odorico, P., Davis, K. F., Rosa, L., Carr, J. A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G. K., Seekell, D. A., Suweis, S., & Rulli, M. C. (2018). The Global Food-Energy-Water Nexus. *Reviews of Geophysics*, *56*(3), 456–531. https://doi.org/10.1029/2017RG000591

D'Odorico, P., & Rulli, M. C. (2013). The fourth food revolution. *Nature Geoscience 2013 6:6*, *6*(6), 417–418. https://doi.org/10.1038/ngeo1842

Döll, P., Müller Schmied, H., Schuh, C., Portmann, F. T., & Eicker, A. (2014). Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. *Water Resources Research*, *50*(7), 5698–5720. https://doi.org/10.1002/2014WR015595

dos Santos, M. J. P. L. (2018). Nowcasting and forecasting aquaponics by Google Trends in European countries. *Technological Forecasting and Social Change*, *134*, 178–185. https://doi.org/10.1016/J.TECHFORE.2018.06.002

Droogers, P., Immerzeel, W. W., Terink, W., Hoogeveen, J., Bierkens, M. F. P., van Beek, L. P. H., & Debele, B. (2012). Water resources trends in Middle East and North Africa towards 2050. *Hydrology and Earth System Sciences*, *16*(9), 3101–3114. https://doi.org/10.5194/HESS-16-3101-2012

DTE. (2016, November 24). *Climate change impact: Morocco counts on renewable energy to reduce CO2 emission*. Down to Earth News. https://www.downtoearth.org.in/news/climate-change/morocco-on-track-to-expand-renewable-energy-projects-to-meet-climate-goals-56419

Dube, T., Moyo, P., Ncube, M., & Nyathi, D. (2016). The Impact of Climate Change on Agro-Ecological Based Livelihoods in Africa: A Review. *Journal of Sustainable Development*, *9*(1). https://doi.org/10.5539/jsd.v9n1p256

EEAA. (2018). Biennial Update Report to the United Nations Framework Convention on Climate Change (UNFCCC). In *Ministry of Environment, Egyptian Environmental Affairs Agency*. www.eeaa.gov.eg

EIA. (2019, November 7). *International - Sudan*. U.S. Energy Information Administration (EIA). https://www.eia.gov/international/analysis/country/SDN

El, A., Berjawi, H., & Spataru, C. (2016). *Implications of the water-energy-land nexus in Egypt under different climatic scenarios Trilemma Evaluation of Whole Integrated Energy Systems in the UK View project Implications of the water-energy-land nexus in Egypt under different climatic scenarios*. https://doi.org/10.13140/RG.2.2.11923.94241

El-Bably, A. Z., & Abd El-Hafez, S. A. (2019). A Strategic Framework for Sustainable Agriculture Development Goals Based On: Water, Energy, Food Security Nexus. *International Journal of Water Resources and Arid Environments*, *8*(2), 118–131.

Elbasiouny, H., Elbanna, B. A., Al-Najoli, E., Alsherief, A., Negm, S., Abou El-Nour, E., Nofal, A., & Sharabash, S. (2020). Agricultural Waste Management for Climate Change Mitigation: Some Implications to Egypt. *Springer Water*, 149–169. https://doi.org/10.1007/978-3-030-18350-9_8/TABLES/2

Elkazzaz, A., El-Kazzaz, K. A., & El-Kazzaz, A. A. (2017). *Soilless Agriculture a New and Advanced Method for Agriculture Development: an Introduction*. https://doi.org/10.19080/ARTOAJ.2017.03.555610

El-Nahrawy, M. A. (2011). Country Pasture/Forage Resource Profiles: Egypt. *United Nations Food and Agriculture Organization (FAO)* . https://docplayer.net/47325686-Country-pasture-forage-resource-profiles-egypt-by-dr-mohamed-a-el-nahrawy.html

El-Rawy, M., Abdalla, F., & el Alfy, M. (2020). Water Resources in Egypt. In Z. Hamimi, A. El-Barkooky, J. Martínez Frías, H. Fritz, & Y. Abd El-Rahman (Eds.), *The Geology of Egypt* (pp. 687–711). Springer, Cham. https://doi.org/10.1007/978-3-030-15265-9_18

Emam, A. R., Kappas, M., & Hosseini, S. Z. (2015). Assessing the impact of climate change on water resources, crop production and land degradation in a semi-arid river basin. *Hydrology Research*, *46*(6), 854–870. https://doi.org/10.2166/NH.2015.143

Falkenmark, M. (2013). Adapting to climate change: towards societal water security in dry-climate countries. *Https://Doi.Org/10.1080/07900627.2012.721714*, *29*(2), 123–136. https://doi.org/10.1080/07900627.2012.721714

FAO. (2009, March). *Growing more food, using less water*. United Nations Food and Agriculture Organization (FAO) . https://www.fao.org/fileadmin/user_upload/newsroom/docs/water_facts.pdf

FAO. (2011). The state of the world’s land and water resources for food and agriculture (SOLAW) – Managing systems at risk. In *Food and Agriculture Organization of the United Nations, Rome and Earthscan, London*. Food and Agriculture Organization of the United Nations, Rome and Earthscan, London.

FAO. (2016). The State of Food and Agriculture: Climate change, agriculture and food security. *Food and Agriculture Organization of the United Nations (FAO)*. www.fao.org/publications

FAO. (2017). The future of food and agriculture and challenges. *Food and Agriculture Organization of the United Nations*.

FAO. (2018, October 16). *Solar powered irrigation: climate-friendly, reliable and affordable*. Food and Agriculture Organization of the United Nations. https://www.fao.org/neareast/news/view/en/c/1158041/

FAO. (2020). *Realizing the Potential and Managing the Risks of Solar Irrigation in the Near East and North Africa*. https://www.fao.org/publications/card/en/c/CB1266EN/

FAO. (2021). *The Sudan: Agricultural livelihoods and food security in the context of COVID-19 - Monitoring report*. https://reliefweb.int/sites/reliefweb.int/files/resources/cb5535en.pdf

FAO AQUASTAT. (2022, April 26). *AQUASTAT database* . The Food and Agriculture Organization of the United Nations. https://www.fao.org/aquastat/statistics/query/index.html;jsessionid=B3597BB4997A53CC700198B4083DD66D

FAO, ECA, & AUC. (2021). Africa – Regional Overview of Food Security and Nutrition 2021OVERVIEW OF FOOD SECURITY AND NUTRITION AFRICA STATISTICS AND TRENDS. *Food and Agriculture Organization*. https://doi.org/10.4060/cb7496en

Fawzy, Z. F., & Shedeed, S. I. (2020). Climate Smart Agriculture and Intelligent Irrigation System for Management of Water Resources in Arid and Semi-Arid Regions – A Review. *Water, Flood Management and Water Security Under a Changing Climate*, 361–370. https://doi.org/10.1007/978-3-030-47786-8_25

Faysse, N. (2015). The rationale of the Green Morocco Plan: missing links between goals and implementation. *The Journal of North African Studies* , *20*(4), 622–634. https://doi.org/10.1080/13629387.2015.1053112

Fobissie, K., & Shalaby, H. (2021). NDC implementation in Egypt through green investments by private sector: A scoping study. In *The African Development Bank*. https://africandchub.org/sites/default/files/2021-06/Egypt%20scoping%20study_05.03_Final.pdf

Frascari, D., Zanaroli, G., Motaleb, M. A., Annen, G., Belguith, K., Borin, S., Choukr-Allah, R., Gibert, C., Jaouani, A., Kalogerakis, N., Karajeh, F., Ker Rault, P. A., Khadra, R., Kyriacou, S., Li, W. T., Molle, B., Mulder, M., Oertlé, E., & Ortega, C. V. (2018). Integrated technological and management solutions for wastewater treatment and efficient agricultural reuse in Egypt, Morocco, and Tunisia. *Integrated Environmental Assessment and Management*, *14*(4), 447–462. https://doi.org/10.1002/IEAM.4045

Gabr, M. (2020). A Roadmap for Establishment of an Early Warning System for Nile Water Quality in Egypt. *Port-Said Engineering Research Journal*, *0*(0), 0–0. https://doi.org/10.21608/PSERJ.2020.18756.1014

Gad, W. A. (2017). Water Scarcity in Egypt: Causes and Consequences. *Institute of Integrative Omics and Applied Biotechnology Journal (IIOABJ), 8*, 40–47. www.iioab.org

Gebru, T. A., Brhane, G. K., & Gebremedhin, Y. G. (2021). Contributions of water harvesting technologies intervention in arid and semi-arid regions of Ethiopia, in ensuring households' food security, Tigray in focus. *Journal of Arid Environments, 185*. https://doi.org/10.1016/J.JARIDENV.2020.104373

Ghafoori-Kharanagh, S., Banihabib, M. E., Javadi, S., & Randhir, T. O. (2021). Participatory Water-Food-Energy Nexus Approach for Evaluation and Design of Groundwater Governance. *Water Resources Management*, *35*(11), 3481–3495. https://doi.org/10.1007/S11269-021-02894-4/FIGURES/7

Gray, S. A., Gray, S., Cox, L. J., & Henly-Shepard, S. (2013). Mental Modeler: A fuzzy-logic cognitive mapping modeling tool for adaptive environmental management. *Proceedings of the Annual Hawaii International Conference on System Sciences*, 965–973. https://doi.org/10.1109/HICSS.2013.399

Gude, V. G. (2017). Desalination and water reuse to address global water scarcity. *Reviews in Environmental Science and Biotechnology*, *16*(4), 591–609. https://doi.org/10.1007/S11157-017-9449-7/TABLES/5

Gupta, G. S. (2019). Land Degradation and Challenges of Food Security. *Review of European Studies, 11*. https://heinonline.org/HOL/Page?handle=hein.journals/rveurost11&id=63&div=&collection=

Gu, Y., Li, Y., Li, X., Luo, P., Wang, H., Robinson, Z. P., Wang, X., Wu, J., & Li, F. (2017). The feasibility and challenges of energy self-sufficient wastewater treatment plants. *Applied Energy, 204*, 1463–1475. https://doi.org/10.1016/J.APENERGY.2017.02.069

GWP. (2022, January 10). *Make Investment in Africa Water Security a Priority in 2022 - GWP*. Global Water Partnership. https://www.gwp.org/en/GWP-SouthernAfrica/About-GWP-SAF/more/News/make-investment-in-africa-water-security-a-priority-in-2022/

Hartung, H. (2018). The benefits and risks of solar-powered irrigation-a global overview Published by the Food and Agriculture Organization of the United Nations and Deutsche Gesellschaft für Internationale Zusammenarbeit. *Food and Agriculture Organization of the United Nations and Deutsche Gesellschaft Für Internationale Zusammenarbeit*. www.fao.org/publications

Hoekstra, A. Y., Buurman, J., & van Ginkel, K. C. H. (2018). Urban water security: A review. *Environmental Research Letters*, *13*(5), 053002. https://doi.org/10.1088/1748-9326/AABA52

Hoff, H. (2011). Understanding the Nexus. *Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environmental Institute*.

Hoff, H., Alrahaife, S. A., el Hajj, R., Lohr, K., Mengoub, F. E., Farajalla, N., Fritzsche, K., Jobbins, G., özerol, G., Schultz, R., & Ulrich, A. (2019). A nexus approach for the

MENA region-from concept to knowledge to action. *Frontiers in Environmental Science*, *7*(APR), 48. https://doi.org/10.3389/FENVS.2019.00048/BIBTEX

Hofste, R. W., Reig, P., & Schleifer, L. (2019, August 6). *17 Countries, Home to One-Quarter of the World's Population, Face Extremely High Water Stress | World Resources Institute*. World Resources Institute (WRI). https://www.wri.org/insights/17-countries-home-one-quarter-worlds-population-face-extremely-high-water-stress

Hossain, M. A., Hassan, M. S., Mottalib, M. A., & Hossain, M. (2015). Feasibility of solar pump for sustainable irrigation in Bangladesh. *International Journal of Energy and Environmental Engineering*, *6*(2), 147–155. https://doi.org/10.1007/S40095-015-0162-4/FIGURES/3

https://www.mentalmodeler.com/. (n.d.). *Mental Modeler - Fuzzy Logic Cognitive Mapping*. Retrieved June 12, 2022, from https://www.mentalmodeler.com/scenario/#

IAMC. (2020, July 3). *COFFEE – Computable Framework For Energy and the Environment model – iamconsortium*. The Integrated Assessment Consortium (IAMC). https://www.iamconsortium.org/uncategorized/computable-framework-for-energy-and-the-environment-model-coffee/

Ibrahim, M., Al-Zyoud, S., Elhaddad, E., Ibrahim, M., Al-Zyoud, S., & Elhaddad, E. (2018). Surface Water Quality Monitoring for River Nile, Egypt Using GIS-Techniques. *Open Journal of Geology*, *8*(2), 161–173. https://doi.org/10.4236/OJG.2018.82010

IEA. (2015). World Outlook Energy 2015. In *International Energy Agency*. www.iea.org/t&c

IEA. (2016). World Energy Outlook 2016. In *International Energy Agency*.

IEA. (2020). Clean Energy Transitions in North Africa. *Clean Energy Transitions in North Africa*. https://doi.org/10.1787/EB8FDD06-EN

IEA. (2021, August). *Africa – World Energy Balances: Overview – Analysis* . Statistics Report - International Energy Agency. https://www.iea.org/reports/world-energy-balances-overview/africa

IFC. (2020a, July 14). *IFC Helps Boost Clean Tech Start-ups in Egypt, Enables Farmers to Switch to Solar*. International Finance Corporation. https://pressroom.ifc.org/all/pages/PressDetail.aspx?ID=18591

IFC. (2020b, November 19). *IFC, Agricultural Bank of Egypt Partner to Promote Farmers' Switch to Solar Irrigation Systems*. International Finance Corporation-World Bank Group. https://pressroom.ifc.org/all/pages/PressDetail.aspx?ID=26078

IIASA. (2021, September 27). *Global Hydro-economic Model (ECHO)* . International Institute for Applied Systems Analysis (IIASA). https://previous.iiasa.ac.at/web/home/research/researchPrograms/water/Global_Hydro-economic_Model.html

India Water Portal. (2022, March 16). *From SPaRC to SKY: Lessons from Gujarat's solar journey | India Water Portal*. https://www.indiawaterportal.org/solar-irrigation/media-library/sparc-sky-lessons-gujarats-solar-journey

Ingram, J. (2011). A food systems approach to researching food security and its interactions with global environmental change. *Food Security*, *3*(4), 417–431. https://doi.org/10.1007/S12571-011-0149-9/FIGURES/5

International Crisis Group. (2019). Bridging the Gap in the Nile Waters Dispute. *Africa Report N°271* .

IPC. (2021). *Sudan: Acute Food Insecurity Situation April - May 2021 and Projections for June - September 2021 and October 2021 - February 2022 | IPC Global Platform*. The Integrated Food Security Phase Classification . https://www.ipcinfo.org/ipc-country-analysis/details-map/en/c/1154879/?iso3=SDN

IRENA, & FAO. (2021). Renewable energy for agri-food systems Towards the Sustainable Development Goals and the Paris Agreement. In *The International Renewable Energy Agency (IRENA) and the Food and Agriculture Organization of the United Nations (FAO)*. https://doi.org/10.4060/cb7433en

ITA. (2020, December 10). *Morocco - Agricultural Sector*. International Trade Administration. https://www.trade.gov/country-commercial-guides/morocco-agricultural-sector

IWMI. (2016). World's First Solar Irrigation Cooperative Receives Award. *International Water Management Institute*, *2021*(197). https://doi.org/10.5337/2021.201

Jetter, A. J., & Kok, K. (2014). Fuzzy Cognitive Maps for futures studies—A methodological assessment of concepts and methods. *Futures*, *61*, 45–57. https://doi.org/10.1016/J.FUTURES.2014.05.002

Johnson, N., Burek, P., Byers, E., Falchetta, G., Flörke, M., Fujimori, S., Havlik, P., Hejazi, M., Hunt, J., Krey, V., Langan, S., Nakicenovic, N., Palazzo, A., Popp, A., Riahi, K., van Dijk, M., van Vliet, M. T. H., van Vuuren, D. P., Wada, Y., … Parkinson, S. (2019). Integrated Solutions for the Water-Energy-Land Nexus: Are Global Models Rising to the Challenge? *Water 2019, Vol. 11, Page 2223*, *11*(11), 2223. https://doi.org/10.3390/W11112223

Kahil, T., Parkinson, S., Satoh, Y., Greve, P., Burek, P., Veldkamp, T. I. E., Burtscher, R., Byers, E., Djilali, N., Fischer, G., Krey, V., Langan, S., Riahi, K., Tramberend, S., & Wada, Y. (2018). A Continental-Scale Hydroeconomic Model for Integrating Water-Energy-Land Nexus Solutions. *Water Resources Research*, *54*(10), 7511–7533. https://doi.org/10.1029/2017WR022478

Kelley, L. C., Gilbertson, E., Sheikh, A., Eppinger, S. D., & Dubowsky, S. (2010). On the feasibility of solar-powered irrigation. *Renewable and Sustainable Energy Reviews*, *14*(9), 2669–2682. https://doi.org/10.1016/J.RSER.2010.07.061

Khalifa, M. M., & Abdelall, M. I. (2019). Ecological desert settlement Egypt western desert. *Alexandria Engineering Journal*, *58*(1), 291–301. https://doi.org/10.1016/J.AEJ.2019.01.003

Khan, M. T. A. I., Sarkar, S., Hossain, S., Ahmed, A. U., & Pathik, B. B. (2014). The feasibility study of solar irrigation: Economical comparison between diesel and photovoltaic water pumping systems for different crops. *2013 International Conference* *on Electrical Information and Communication Technology, EICT 2013*. https://doi.org/10.1109/EICT.2014.6777844

Kim, G.-R. (2009). Analysis of Global Food Market and Food-Energy Price Links: Based on System Dynamics Approach. *Korean System Dynamics Review | Korea Science*, 105–124.

Kok, K. (2009). The potential of Fuzzy Cognitive Maps for semi-quantitative scenario development, with an example from Brazil. *Global Environmental Change*, *19*(1), 122–133. https://doi.org/10.1016/J.GLOENVCHA.2008.08.003

Kokkinos, K., Karayannis, V., & Moustakas, K. (2020). Circular bio-economy via energy transition supported by Fuzzy Cognitive Map modeling towards sustainable low-carbon environment. *Science of The Total Environment*, *721*, 137754. https://doi.org/10.1016/J.SCITOTENV.2020.137754

Kooij, S. van der. (2016). *Performing drip irrigation by the farmer managed Seguia Khrichfa irrigation system, Morocco*. https://doi.org/10.18174/376256

Kosko, B. (1986). Fuzzy cognitive maps. *International Journal of Man-Machine Studies*, *24*(1), 65–75. https://www.academia.edu/1035128/Fuzzy_cognitive_maps_by_Kosko

Kropf, B., Schmid, E., & Mitter, H. (2021). Multi-step cognitive mapping of perceived nexus relationships in the Seewinkel region in Austria. *Environmental Science & Policy*, *124*, 604–615. https://doi.org/10.1016/J.ENVSCI.2021.08.004

Lakhiar, I. A., Gao, J., Syed, T. N., Chandio, F. A., & Buttar, N. A. (2018). Modern plant cultivation technologies in agriculture under controlled environment: a review on aeroponics. *Http://Mc.Manuscriptcentral.Com/Tjpi*, *13*(1), 338–352. https://doi.org/10.1080/17429145.2018.1472308

Leese, M., & Meisch, S. (2015). Securitising Sustainability? Questioning the "Water, Energy and Food-Security Nexus." *Water Alternatives*, *8*(1), 695–709. www.water-alternatives.org

Lefore, N., Closas, A., & Schmitter, P. (2021). Solar for all: A framework to deliver inclusive and environmentally sustainable solar irrigation for smallholder agriculture. *Energy Policy*, *154*. https://doi.org/10.1016/J.ENPOL.2021.112313

Lezzaik, K., Milewski, A., & Mullen, J. (2018). The groundwater risk index: Development and application in the Middle East and North Africa region. *Science of The Total Environment*, *628–629*, 1149–1164. https://doi.org/10.1016/J.SCITOTENV.2018.02.066

Liu, J., Hull, V., Godfray, H. C. J., Tilman, D., Gleick, P., Hoff, H., Pahl-Wostl, C., Xu, Z., Chung, M. G., Sun, J., & Li, S. (2018). Nexus approaches to global sustainable development. *Nature Sustainability*, *1*(9), 466–476. https://doi.org/10.1038/S41893-018-0135-8

Malabo Montpellier Panel. (2019). Energized: Policy innovation to power the transformation of Africa's agriculture and food system: Morocco. *International Food Policy Research Institute*. https://doi.org/10.2499/P15738COLL2.133506

Martinez-Hernandez, E., Leach, M., & Yang, A. (2017). Understanding water-energy-food and ecosystem interactions using the nexus simulation tool NexSym. *Applied Energy*, *206*, 1009–1021. https://doi.org/10.1016/J.APENERGY.2017.09.022

Martinez, P., Blanco, M., & Castro-Campos, B. (2018). The Water–Energy–Food Nexus: A Fuzzy-Cognitive Mapping Approach to Support Nexus-Compliant Policies in Andalusia (Spain). *Water 2018, Vol. 10, Page 664*, *10*(5), 664. https://doi.org/10.3390/W10050664

Martin-Shields, C. P., & Stojetz, W. (2019). Food security and conflict: Empirical challenges and future opportunities for research and policy making on food security and conflict. *World Development*, *119*, 150–164. https://doi.org/10.1016/J.WORLDDEV.2018.07.011

Massuel, S., Amichi, F., Ameur, F., Calvez, R., Jenhaoui, Z., Bouarfa, S., Kuper, M., Habaieb, H., Hartani, T., & Hammani, A. (2017). Prendre en compte l'utilisation des eaux souterraines pour améliorer l'évaluation des pompages d'eaux souterraines pour l'irrigation dans le Nord de l'Afrique. *Hydrogeology Journal*, *25*(6), 1565–1577. https://doi.org/10.1007/S10040-017-1573-5/TABLES/3

McGrane, S. J., Acuto, M., Artioli, F., Chen, P. Y., Comber, R., Cottee, J., Farr-Wharton, G., Green, N., Helfgott, A., Larcom, S., McCann, J. A., O'Reilly, P., Salmoral, G., Scott, M., Todman, L. C., van Gevelt, T., & Yan, X. (2018). Scaling the nexus: Towards integrated frameworks for analysing water, energy and food. *Geographical Journal*, *185*(4), 419–431. https://doi.org/10.1111/GEOJ.12256

Meah, K., Fletcher, S., & Ula, S. (2008). Solar photovoltaic water pumping for remote locations. *Renewable and Sustainable Energy Reviews*, *12*(2), 472–487. https://doi.org/10.1016/J.RSER.2006.10.008

Mergoul, K., Laarabi, B., & Barhdadi, A. (2018). Solar water pumping applications in Morocco: State of the art. *Proceedings of 2018 6th International Renewable and Sustainable Energy Conference, IRSEC 2018*. https://doi.org/10.1109/IRSEC.2018.8703015

Ministerie van Landbouw, N. en V. (2021, April 9). *Morocco allocates US$500m to support agriculture | Nieuwsbericht | Agroberichten Buitenland*. Ministerie van Landbouw Natuur En Voedselkwaliteit, the Netherlands. https://www.agroberichtenbuitenland.nl/actueel/nieuws/2021/04/09/morocco-allocates-ususd500m-to-support-agriculture

Momblanch, A., Papadimitriou, L., Jain, S. K., Kulkarni, A., Ojha, C. S. P., Adeloye, A. J., & Holman, I. P. (2019). Untangling the water-food-energy-environment nexus for global change adaptation in a complex Himalayan water resource system. *Science of the Total Environment*, *655*, 35–47. https://doi.org/10.1016/J.SCITOTENV.2018.11.045

Mostafa, S. M., Wahed, O., El-Nashar, W. Y., El-Marsafawy, S. M., Zeleňáková, M., & Abd-Elhamid, H. F. (2021). Potential Climate Change Impacts on Water Resources in Egypt. *Water 2021, Vol. 13, Page 1715*, *13*(12), 1715. https://doi.org/10.3390/W13121715

Nair, S., George, B., Malano, H. M., Arora, M., & Nawarathna, B. (2014). Water–energy–greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods. *Resources, Conservation and Recycling*, *89*, 1–10. https://doi.org/10.1016/J.RESCONREC.2014.05.007

Netherlands Environmental Assessment Agency. (2021, December 1). *Welcome to IMAGE 3.2 Documentation - IMAGE*. PBL Netherlands Environmental Assessment Agency. https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.2_Documentation

Obiedat, M., & Samarasinghe, S. (2016). A novel semi-quantitative Fuzzy Cognitive Map model for complex systems for addressing challenging participatory real life problems. *Applied Soft Computing Journal*, *48*, 91–110. https://doi.org/10.1016/J.ASOC.2016.06.001

Obirikorang, K. A., Sekey, W., Gyampoh, B. A., Ashiagbor, G., & Asante, W. (2021). Aquaponics for Improved Food Security in Africa: A Review. *Frontiers in Sustainable Food Systems*, *5*, 300. https://doi.org/10.3389/FSUFS.2021.705549/BIBTEX

Odeh, I., Yohanis, Y. G., & Norton, B. (2006). Economic viability of photovoltaic water pumping systems. *Solar Energy*, *80*(7), 850–860. https://doi.org/10.1016/J.SOLENER.2005.05.008

OECD. (2020). “The COVID-19 crisis in Morocco”, Tackling Coronavirus (COVID-19), contributing to a global effort. *Organisation for Economic Co-Operation and Development*.

Olazabal, M., & Pascual, U. (2016). Use of fuzzy cognitive maps to study urban resilience and transformation. *Environmental Innovation and Societal Transitions*, *C*(18), 18–40. https://doi.org/10.1016/J.EIST.2015.06.006

Oluwasanya, G., Perera, D., Qadir, M., & Smakhtin, V. (2022). Water Security in Africa: A Preliminary Assessment, issue 13. In *United Nations University Institute for Water, Environment and Health, Hamilton, Canada*. https://reliefweb.int/report/niger/water-security-africa-preliminary-assessment

Omer, A. M. (2001). Solar water pumping clean water for Sudan rural areas. *Renewable Energy*, *24*(2), 245–258. https://doi.org/10.1016/S0960-1481(00)00095-1

Omer, A. M. (2007). Renewable energy resources for electricity generation in Sudan. *Renewable and Sustainable Energy Reviews*, *11*(7), 1481–1497. https://doi.org/10.1016/J.RSER.2005.12.001

Osman Elzubeir, A. (2016). Current State and Prospects. *Asim Osman Elzubeir. Solar Energy in Northern State*, *2*(5), 31–37. https://doi.org/10.11648/j.ajme.20160205.12

Özesmi, U., & Özesmi, S. L. (2004). Ecological models based on people’s knowledge: A multi-step fuzzy cognitive mapping approach. *Ecological Modelling*, *176*(1–2), 43–64. https://doi.org/10.1016/J.ECOLMODEL.2003.10.027

Palit, D., Govindan, M., & Murali, R. (2021). *Implementing Solar Irrigation Sustainably: A guidebook for state policy- makers on maximizing the social and environmental benefits from solar pump schemes*. https://www.researchgate.net/publication/357368397_Implementing_Solar_Irrigation_Sustainably_A_guidebook_for_state_policy-

_makers_on_maximizing_the_social_and_environmental_benefits_from_solar_pump_schemes

Parvaresh Rizi, A., Ashrafzadeh, A., & Ramezani, A. (2019). A financial comparative study of solar and regular irrigation pumps: Case studies in eastern and southern Iran. *Renewable Energy, 138,* 1096–1103. https://doi.org/10.1016/J.RENENE.2019.02.026

PNNL. (2022). *Integrated Multisector Multiscale Modeling (IM3)*. Pacific Northwest National Laboratory, United States. https://im3.pnnl.gov/

Polak, P., & Yoder, R. (2006). Creating wealth from groundwater for dollar-a-day farmers: Where the silent revolution and the four revolutions to end rural poverty meet. *Hydrogeology Journal*, *14*(3), 424–432. https://doi.org/10.1007/S10040-005-0011-2/FIGURES/2

Power Sector Reform Programme (PSRP). (2021). Facilitating remote monitoring of solar pumps. *KPMG*. https://www.linkedin.com/company/psr-india

Purwanto, A., Sušnik, J., Suryadi, F. X., & de Fraiture, C. (2019). Using group model building to develop a causal loop mapping of the water-energy-food security nexus in Karawang Regency, Indonesia. *Journal of Cleaner Production*, *240*, 118170. https://doi.org/10.1016/J.JCLEPRO.2019.118170

Raditloaneng, W. N. (2012). Socio- Economic Factors in Rural Water Scarcity: A Case Study of Molepolole Village in Botswana. *American Journal of Human Ecology*, *1*(3), 95–101. https://doi.org/10.11634/216796221504193

Raleigh, C., & Kniveton, D. (2012). Come rain or shine: An analysis of conflict and climate variability in East Africa. *Journal of Peace Research*, *49*(1), 51–64. https://doi.org/10.1177/0022343311427754

Ramadan, R. (2015). Food Security and its Measurement in Egypt . *International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM)*, *4*.

Ramos, E. P., Howells, M., Sridharan, V., Engström, R. E., Taliotis, C., Mentis, D., Gardumi, F., de Strasser, L., Pappis, I., Balderrama, G. P., Almulla, Y., Beltramo, A., Ramirez, C., Sundin, C., Alfstad, T., Lipponen, A., Zepeda, E., Niet, T., Quirós-Tortós, J., … Rogner, H. (2021). The climate, land, energy, and water systems (CLEWs) framework: A retrospective of activities and advances to 2019. *Environmental Research Letters*, *16*(3). https://doi.org/10.1088/1748-9326/ABD34F

Ramsey, A., & Mustard, A. (2012, November 8). *An Egyptian startup wants to move farmers into the sun and away from the Nile — Quartz*. https://qz.com/16295/an-egyptian-startup-wants-to-move-farmers-into-the-sun-and-away-from-the-nile/

Reda, L. (2019, March 1). The solar-powered irrigation scene in Egypt - EgyptToday. *Egypt Today: The Magazine of Egypt*. https://www.egypttoday.com/Article/3/66436/The-solar-powered-irrigation-scene-in-Egypt

Rezk, H. (2016). A comprehensive sizing methodology for stand-alone battery-less photovoltaic water pumping system under the Egyptian climate. *Cogent Engineering*, *3*(1). https://doi.org/10.1080/23311916.2016.1242110

Ringler, C., Mekonnen, D., Xie, H., & Uhunamure, A. M. (2020). Irrigation to Transform Agriculture and Food Systems in Africa South of the Sahara. In Anthony J. Jakeman, Olivier Barreteau, & Randall J. Hunt Jean-Daniel Rinaudo Andrew Ross (Eds.), *2020 Annual trends and outlook report: Sustaining Africa's agrifood system transformation: The role of public policies*. INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE (IFPRI)AKADEMIYA2063. https://doi.org/https://doi.org/10.2499/9780896293946

Rochedo, P. R. R. (2016). *Development of a global integrated energy model to evaluate the brazilian role in climate change mitigation scenarios*. The Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering (COPPE/UFRJ).

Rost, S., Gerten, D., Hoff, H., Lucht, W., Falkenmark, M., & Rockström, J. (2009). Global potential to increase crop production through water management in rainfed agriculture. *Environmental Research Letters*, *4*(4). https://doi.org/10.1088/1748-9326/4/4/044002

Salman, M., Abdelfattah, A., Ahmad, W., & Simongini, C. (2022). The use of solar energy in irrigated agriculture: A sourcebook for irrigation water management with alternative energy solutions. *Food and Agriculture Organization of the United Nations*. https://doi.org/10.4060/cb8459en

Sampaio, P. G. V., & González, M. O. A. (2017). Photovoltaic solar energy: Conceptual framework. *Renewable and Sustainable Energy Reviews*, *74*, 590–601. https://doi.org/10.1016/J.RSER.2017.02.081

Savvas, D. (2003). Hydroponics: A modern technology supporting the application of integrated crop management in greenhouse-Web of Science Core Collection. *Journal of Food Agriculture and Environment*, *1*(1), 80–86. https://www-webofscience-com.ezproxy2.utwente.nl/wos/woscc/full-record/WOS:000208574700013

Schaer, C. (2021, April 28). *How Yemen's solar power revolution could drain the whole country of water | Middle East | News and analysis of events in the Arab world | DW | 28.04.2021*. https://www.dw.com/en/how-yemens-solar-power-revolution-could-drain-the-whole-country-of-water/a-57364390

Schilling, J., Hertig, E., Tramblay, Y., & Scheffran, J. (2020). Climate change vulnerability, water resources and social implications in North Africa. *Regional Environmental Change*, *20*(1), 1–12. https://doi.org/10.1007/S10113-020-01597-7/FIGURES/4

SEI. (2021, February). *WEAP: Water Evaluation And Planning System*. Stockholm Environment Institute. https://www.weap21.org/index.asp?NewLang=EN

Senol, R. (2012). An analysis of solar energy and irrigation systems in Turkey. *Energy Policy*, *47*, 478–486. https://doi.org/10.1016/J.ENPOL.2012.05.049

Shah, T., Durga, N., Verma, S., & Rathod, R. (2016). Solar Power as Remunerative Crop. *Water Policy Research Highlight*, *10*. www.iexindia.com

Shah, T., Rajan, A., Rai, G. P., Verma, S., & Durga, N. (2018). Solar pumps and South Asia's energy-groundwater nexus: exploring implications andreimagining its future. *Environ. Res. Lett*, *13*, 115003. https://doi.org/10.1088/1748-9326/aae53f

Shannak, S., Mabrey, D., & Vittorio, M. (2018). Moving from theory to practice in the water–energy–food nexus: An evaluation of existing models and frameworks. *Water-Energy Nexus*, *1*(1), 17–25. https://doi.org/10.1016/J.WEN.2018.04.001

Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F. T. (2010). Groundwater use for irrigation - A global inventory. *Hydrology and Earth System Sciences*, *14*(10), 1863–1880. https://doi.org/10.5194/HESS-14-1863-2010

Simmers, I. (2003). *Understanding water in a dry environment : hydrological processes in arid and semi-arid zones*. 341.

Simpson, G. B., & Jewitt, G. P. W. (2019). The development of the water-energy-food nexus as a framework for achieving resource security: A review. *Frontiers in Environmental Science*, *7*(FEB), 8. https://doi.org/10.3389/FENVS.2019.00008/BIBTEX

Skaggs, R., Hibbard, K. A., Frumhoff, P., Lowry, T., Middleton, R., Pate, R., Tidwell, V. C., Arnold, J. G., Averyt, K., Janetos, A. C., Izaurralde, R. C., Rice, J. S., & Rose, S. K. (2012). *Climate and Energy-Water-Land System Interactions Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment*. https://doi.org/10.2172/1040680

Solana-Gutiérrez, J., Rincón, G., Alonso, C., & García-de-Jalón, D. (2017). Using fuzzy cognitive maps for predicting river management responses: A case study of the Esla River basin, Spain. *Ecological Modelling*, *360*, 260–269. https://doi.org/10.1016/J.ECOLMODEL.2017.07.010

Solar water irrigation system. (2021, April 1). https://satvikkoorja.com/solar-water-irrigation-system/

Soliman, A. M. M., & Solimsn, M. M. (2019). Groundwater potential in the new valley south west of the nile delta in Egypt. *Handbook of Environmental Chemistry*, *73*, 585–621. https://doi.org/10.1007/698_2017_62/TABLES/11

Soliman, A., Nassar, A., & Sattar, A. (2017). Cost Analysis for Irrigation Projects Using Solar Energy in Egypt. *International Journal of Scientific & Engineering Research*, *8*(9). http://www.ijser.org

Sullivan, P. J. (2010, January 8). *Perspective: Sudan - Land of Water and Thirst; War and Peace - Circle of Blue*. Circle of Blue: Where Water Speaks. https://www.circleofblue.org/2010/world/perspective-sudan-land-of-water-and-thirst-war-and-peace/

Sušnik, J., & Staddon, C. (2021). Evaluation of Water-Energy-Food (WEF) Nexus Research: Perspectives, Challenges, and Directions for Future Research. *Journal of the American Water Resources Association*. https://doi.org/10.1111/1752-1688.12977

Swain, A. (2011). Challenges for water sharing in the Nile basin: changing geo-politics and changing climate. *Hydrological Sciences Journal*, *56*(4), 687–702. https://doi.org/10.1080/02626667.2011.577037

Tadese, J. (2020, February). *The Grand Ethiopian Renaissance Dam (GERD): Diplomatic War Between Ethiopia and Egypt*. Alice Salomon Hochschule Berlin.

https://www.researchgate.net/publication/351256854_The_Grand_Ethiopian_Renaissance_Dam_GERD_Diplomatic_War_Between_Ethiopia_and_Egypt

Tawfeek, F. (2018, September 6). *UN to help provide Egypt solar energy, underground irrigation - Egypt Independent*. Egypt Independent. https://www.egyptindependent.com/un-to-help-provide-egypt-solar-energy-underground-irrigation/

Taylor, I. (2015). Dependency redux: why Africa is not rising. *Https://Doi.Org/10.1080/03056244.2015.1084911*, *43*(147), 8–25. https://doi.org/10.1080/03056244.2015.1084911

Tellioglu, I., & Konandreas, P. (2017). Agricultural Policies, Trade and Sustainable Development in Egypt. *International Centre for Trade and Sustainable Development (ICTSD)*. www.ictsd.org

Trainer, T. (2013). Can Europe run on renewable energy? A negative case. *Energy Policy*, *63*, 845–850. https://doi.org/10.1016/J.ENPOL.2013.09.027

Tsang, M. P., Sonnemann, G. W., & Bassani, D. M. (2016). Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies. *Solar Energy Materials and Solar Cells*, *156*, 37–48. https://doi.org/10.1016/J.SOLMAT.2016.04.024

UNDP. (2019, May 21). *UNDP, KOICA Partner in Project to Promote Solar-Powered Irrigation for Sustainable Agriculture in Sudan | UNDP in Sudan*. United Nations Development Programme . https://www.sd.undp.org/content/sudan/en/home/presscenter/pressreleases/2019/UNDP-and-KOICA-Partner-in-Project-to-Promote-Solar-Powered-Irrigation-for-Sustainable-Agriculture-in-Sudan.html

UNDP. (2022, June 5). *Transforming Egypt's energy market* . | United Nations Development Programme. https://www.undp.org/arab-states/stories/transforming-egypt%E2%80%99s-energy-market

UNFCCC. (2020, October). *Climate Change Is an Increasing Threat to Africa* . United Nations Framework Convention on Climate Change. https://unfccc.int/news/climate-change-is-an-increasing-threat-to-africa

UNICEF. (2020, August 22). *"Running Dry": unprecedented scale and impact of water scarcity in the Middle East and North Africa*. The United Nations International Children's Emergency Fund. https://www.unicef.org/press-releases/running-dry-unprecedented-scale-and-impact-water-scarcity-middle-east-and-north

University of Oxford. (2022). *NexSym - academic*. Oxford University Innovation. https://process.innovation.ox.ac.uk/software/p/16137a/nexsym-academic/1

UNSD. (2022). *Methodology - Standard country or area codes for statistical use*. United Nations Statistics Division. https://unstats.un.org/unsd/methodology/m49/#geo-regions

USAID. (2015). Greenhouse Gas (GHG) Emissions in Egypt . *The United States Agency for International Development*. http://www.lse.ac.uk/GranthamInstitute/legislation/countries/egypt/.

USAID. (2016). Greenhouse gas emissions: Morocco. *The United States Agency for International Development*. https://www.iea.org/publications/freepublications/publication/Morocco2014.pdf

USAID. (2017). Greenhouse Gas (GHG) Emissions in Sudan. *The United States Agency for International Development*.

USAID. (2018, October). *Climate Risk Profile: Egypt fact sheet*. The United States Agency for International Development. https://reliefweb.int/sites/reliefweb.int/files/resources/2018_USAID-ATLAS-Project_Climate-Risk-Profile-Egypt.pdf

USAID. (2022, April 18). *Egypt Fact Sheet: Agriculture*. The United States Agency for International Development. https://www.usaid.gov/sites/default/files/documents/EG-Ag_Sector_EN_2022.pdf

van Vuuren, D. P., Bijl, D. L., Bogaart, P., Stehfest, E., Biemans, H., Dekker, S. C., Doelman, J. C., Gernaat, D. E. H. J., & Harmsen, M. (2019). Integrated scenarios to support analysis of the food–energy–water nexus. *Nature Sustainability*, *2*(12), 1132–1141. https://doi.org/10.1038/S41893-019-0418-8

Verma, S. (2020). Solar pump cooperative supports climate-smart agriculture in Gujarat. *The Climate and Development Knowledge Network (CDKN*. www.cdkn.org

Verma, S., Durga, N., & Shah. Tushaar. (2016). *Solar Power as Remunerative Crop (SPaRC)*. https://www.researchgate.net/project/Solar-Power-as-Remunerative-Crop-SPaRC

Verschuren, P., & Doorewaard, H. (2010). *Designing a Research Project*.

Vinca, A., Riahi, K., Rowe, A., & Djilali, N. (2021). Climate-Land-Energy-Water Nexus Models Across Scales: Progress, Gaps and Best Accessibility Practices. *Frontiers in Environmental Science*, *9*, 252. https://doi.org/10.3389/FENVS.2021.691523/BIBTEX

Voisin, N., Dyreson, A., Fu, T., O'Connell, M., Turner, S. W. D., Zhou, T., & Macknick, J. (2020). Impact of climate change on water availability and its propagation through the Western U.S. power grid. *Applied Energy*, *276*, 115467. https://doi.org/10.1016/J.APENERGY.2020.115467

Vora, N., Shah, A., Bilec, M. M., & Khanna, V. (2017). Food-Energy-Water Nexus: Quantifying Embodied Energy and GHG Emissions from Irrigation through Virtual Water Transfers in Food Trade. *ACS Sustainable Chemistry and Engineering*, *5*(3), 2119–2128. https://doi.org/10.1021/ACSSUSCHEMENG.6B02122/SUPPL_FILE/SC6B02122_SI_001.PDF

Wada, Y., van Beek, L. P. H., Sperna, F. C., Chao, B. F., Wu, Y.-H., Bierkens, M. F. P., van Beek, L. P. H., Sperna, F. C., Chao, B. F., Wu, Y.-H., & Bierkens, M. F. P. (2012). Past and future contribution of global groundwater depletion to sea-level rise. *Geophysical Research Letters*, *39*(9). https://doi.org/10.1029/2012GL051230

Wang, W., & Duffy, A. (2009, August). A Triangulation Approach for Design Research. *International Conference on Engineering Design*.

WaterWorld. (2018, December 26). *Xylem monitoring technology helps protect Nile River from pollution | WaterWorld*. https://www.waterworld.com/drinking-water/distribution/article/16203354/xylem-monitoring-technology-helps-protect-nile-river-from-pollution

WEF. (2011, January 24). *Water Security: The Water-Energy-Food-Climate Nexus | World Economic Forum*. World Economic Forum Initiative. https://www.weforum.org/reports/water-security-water-energy-food-climate-nexus

WEF NEXUS Tool 2.0. (2014). Nano Technologies LTD. http://wefnexustool.org/user.php

Wegerich, K., Rooijen, D. van, Soliev, I., & Mukhamedova, N. (2015). Water security in the Syr Darya basin. *Water (Switzerland)*, *7*(9), 4657–4684. https://doi.org/10.3390/W7094657

WFP. (2021, June 1). *The Government of Sudan, FAO and WFP call for investment in Sudan's agriculture as number of people facing acute food insecurity reaches record high | World Food Programme*. United Nations World Food Programme. https://www.wfp.org/news/government-sudan-fao-and-wfp-call-investment-sudans-agriculture-number-people-facing-acute

WFP, FAO, IFAD, & UNICEF. (2017). *The State of Food Security and Nutrition in the World 2017. Building Resilience for Peace and Food Security*. Rome: Food and Agriculture Organization of the United Nations.

White, C. (2014). Understanding water scarcity: Definitions and measurements. *Global Water: Issues and Insights*. https://doi.org/10.22459/GW.05.2014.28

Wichelns, D. (2010). Economic Efficiency and Irrigation Water Policy with an Example from Egypt. *International Journal of Water Resources Development* , *15*(4), 543–560. https://doi.org/10.1080/07900629948754

World Bank. (2018). Kingdom of Morocco - Governing Towards Efficiency, Equity, Education and Endurance: A Systematic Country Diagnostic. *World Bank Group*.

World Bank. (2020). *Egypt - Climatology | Climate Change Knowledge Portal*. World Bank Group: Climate Change Knowledge Portal. https://climateknowledgeportal.worldbank.org/country/egypt/climate-data-historical

World Bank. (2021, January 29). *Employment in agriculture (% of total employment) (modeled ILO estimate) | Data*. International Labour Organization, ILOSTAT Database. https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS

World Population Review. (2022). *Population by Continent 2022*. https://worldpopulationreview.com/continents

WRI. (2021, April 1). *Egypt: Transitioning Away from Subsidizing Fossil Fuels*. World Resource Institute; Cambridge University Press. https://doi.org/10.1017/9781108241946.017

WRI CAIT. (2014, April 10). *Climate Watch (CAIT): Country Greenhouse Gas Emissions Data*. World Resources Institute Climate Watch. https://www.wri.org/data/climate-watch-cait-country-greenhouse-gas-emissions-data

Xie, H., Ringler, C., & Mondal, M. A. H. (2021). Solar or Diesel: A Comparison of Costs for Groundwater-Fed Irrigation in Sub-Saharan Africa Under Two Energy Solutions. *Earth's Future*, *9*(4), e2020EF001611. https://doi.org/10.1029/2020EF001611

Zamani, M. G., Moridi, A., & Yazdi, J. (2022). Groundwater management in arid and semi-arid regions. *Arabian Journal of Geosciences*, *15*(4). https://doi.org/10.1007/S12517-022-09546-W

Zhong, S., Zhu, Y., Zhao, J., & Shen, L. (2022). A Collaborative Framework for Hydropower Development and Sustainable Livelihood of Farmers in the Lancang-Mekong River Basin: A Review with the Perspective of Energy-Water-Food Nexus. *Water (Switzerland)*, *14*(3). https://doi.org/10.3390/W14030499

Ziv, G., Watson, E., Young, D., Howard, D. C., Larcom, S. T., & Tanentzap, A. J. (2018). The potential impact of Brexit on the energy, water and food nexus in the UK: A fuzzy cognitive mapping approach. *Applied Energy*, *210*, 487–498. https://doi.org/10.1016/J.APENERGY.2017.08.033

APPENDIX A

QUESTIONNAIRE/ INTERVIEW GUIDE

Introduction

- Introduce myself
- State the aim of the research and interview
- Confirm whether the information from the interview can be recorded and used for the interview

General Questions

1 What is your job position and your responsibilities/interests?

2 Which sector are you part of or which sector do you work for? How experienced are you with solar pump irrigation (either in the implementation, the technical aspects, how it has been used in the field etc.)?

3 In your opinion, what are the most important synergies and trade-offs of this technology in terms of water for food; energy for water; and energy for food? Could you describe why you think so?

PROJECT IMPLEMENTERS

Project-related

4 What is the duration of the Solar pumps irrigation systems (SPIS) project and how was it funded?

5 In your opinion, what are the water resources generally available in the concerned country?

6 In your opinion, what are the top priority factors considered before the implementation of solar irrigation projects?

7 What are farmers reactions to the use of solar pumps for irrigation, especially when you introduced your projects to them?

9. What are your criteria for selecting farmers' participation?

10. Project A- One of the reports mentioned "water security for farmers" as one of the objectives of the initiative. In what way? And how did the SPIS project impact that?

11. Project B- One of the reports mentioned that "farmers struggle with limited water". In your own opinion, could this be due to the farmers not owning a diesel pump or there is no access to water resources in that region? And how did the SPIS project impact that?

12. Before the implementation of the project, are there consultations with national water resources management institutions?
    (a) If yes, did the consultation poses any challenge to the progress/success of SPIS adoption?
    (b) Are the farmers monitored and guided on the sustainable use of this technology such that water withdrawal do not go overboard?

Evaluative

13. What do you think are the most important advantages of solar pumps over diesel pumps, and the differences between them?
14. Do you think solar pumps should continue to be promoted regardless of the aridity of the area and the available water resources? Why?

AGRICULTURAL WATER MANAGEMENT EXPERTS/RESEARCHERS

Water resources and solar irrigation related

15. In the organizational structure of agricultural water management, are there inclusions that involve monitoring technologies that are related to water resources?
16. From my research on solar pump irrigation systems (SPIS), food security, reduction of greenhouse gases, farmer's livelihood, rural development, access to finance and water availability for farmers are the most important factors to consider while promoting the adoption of solar irrigation systems (SPIS) in arid/semi-arid regions? In your opinion, is this true?
17. What do you think are the most important differences and similarities between solar pumps and diesel pumps?
18. Do you think the promotion/widespread of solar pump irrigation system will worsen the effect of climate change in water-scarce region? Kindly elaborate.

Governance-related

19. In a semi-arid region such as North Africa where agriculture is predominant and food security is an integral challenge, What do you think are the most important variables/aspects to improve on in order to ensure sustainable adoption and governance of solar pump irrigation systems (SPIS) without overexploitation of groundwater?

20. To what extent do you foresee groundwater governance being standardized in agricultural water management policies?
21. Do you think there should be policies that governs the average amount of water withdrawn by farmers as the adoption of SPIS widely spreads?
22. Who do you think should be in charge of monitoring water withdrawals by farmers (municipality, state government of private company) and why?
23. Some researchers think that policies related to different sectors (food, water, and energy) are too siloed, or departmentalized, and this is creating policies that are not effective or unable to connected with the actual situation on the ground—Do you think policies that synergize or coordinate between sectors will benefit the adoption and implementation of SPIS? If so how? Do you know of any cases where this has worked?

Strategies and recommendations related

24. What should be done to ensure that groundwater overexploitation do not worsen as solar pump irrigation is being adopted globally?
25. In your own opinion, which country in N. Africa is leading the way or is demonstrating best practices when it comes to SPIS implementation and governance?
26. What policies and guidelines should ministry of agriculture, water resources management and irrigation put in place to monitor the use of such water withdrawal technology?
27. What policy suggestion do you have for preserving and balancing the use of groundwater at the time of climatic risk such as drought in water stress region like North Africa?
28. What recommendations would you give to reduce over-exploitation of groundwater by farmers using solar pumps?
29. What changes should be made to improve general agricultural water management?

APPENDIX B

INFORMED CONSENT FORM FOR "A NEXUS APPROACH TO SOLAR PUMPING IRRIGATION SYSTEMS IN NORTH AFRICA: OPPORTUNITIES AND CHALLENGES"

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

General information: Agriculture, being a major source of livelihood in North Africa, is shifting towards becoming climate-smart by the introduction of solar-powered water pump irrigation system. This technology is being promoted by government, with funding from other organizations in other to help farmers with the transition from diesel-powered pump to solar pump. On the other hand, the adoption of this technology might be a threat to the sustainable use of groundwater, such that more policies is needed to be adopted in other to minimize this threat.

The aim of this study is to obtain information about the effect of solar pump irrigation system on food and water security in North Africa and to suggest possible ways to adopt the technology more sustainably.

The study was previously approved by the ethics committee of the Department of Behavioural, Management and Social Sciences (BMS for the English abbreviation). The participant is free to withdraw from the research at any time, i.e. during the interview(s) and the writing of the thesis, namely that the information provided, if applicable, is not used or cannot be used or modified by the participant. That being said, it is important to state that any information collected will be used solely for the purpose of answering the research questions and will be protected for the duration of the research, which ends on August, 2022. After that, Once the thesis is published, the only existing information is contained in the document (information that is pre-approved by the participant). In any case, the participation can is anonymous; no names will be shared in the document.

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study/research, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	□	□
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	□	□
I understand that taking part in the study involves **a video or audio-recorded interview or answering a survey. For interview, the information will be transcribed as text and only be used for the research and no other.**	□	□
Risks associated with participating in the study		
I understand that taking part in the study involves the following risks: [Discussing the problems encountered in your SPIS projects]	□	□
Use of the information in the study		
I understand that information I provide will be used to **develop the research results and help answer the research questions**	□	□
I understand that personal information collected about me that can identify me, such as name and address, will not be shared beyond the study team.	□	□
Future use and reuse of the information by others		
I give permission for the *data and information* that I provide to be archived as coded anonymized transcripts or audio recording in a cloud data storage (google drive/one drive) so it can be used for future research and learning.	□	□

Signatures

______________________ ______________________ ______________

Name of participant [printed] Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Popoola Olayemi Deborah

Researcher name [printed] Signature Date

Study contact details for further information: Popoola, Olayemi Deborah, o.d.popoola@student.utwente.nl

Contact Information for Questions about Your Rights as a Research Participant: +31685791792, o.d.popoola@student.utwente.nl

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee/domain Humanities & Social Sciences of the Faculty of Behavioural, Management and Social Sciences at the University of Twente by ethicscommittee-hss@utwente.nl

APPENDIX C

Source: IFC (2020b)

Source: FAO, (2018)

Source: Reda (2019)

APPENDIX D

Combining all the four proposed policy options: