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Overview of solar and wind-driven water pump designs applicable for the arid and semi-arid areas of Africa, Asia, and Latin America

BACHELOR’S THESIS

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Declaration

I hereby declare that I have done this thesis entitled “Overview of solar and wind-driven water pump designs applicable for the arid and semi-arid areas of Africa, Asia, and Latin America” independently, all texts in this thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In Prague, April 18th, 2024

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Danica Juházyová

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I am also deeply grateful for my parents' encouragement, and support, and for ensuring that I am passionate about my academic and research aspirations.

Abstract

This bachelor's thesis offers an overview of the problems associated with water shortages that are common in ten chosen arid and semi-arid countries of Latin America, Africa, and Asia, with an emphasis on sustainable energy solutions. The study examines the complex interaction between energy requirements and water demands in various less developed countries, highlighting the importance of solar and wind energy.

Using a thorough approach based on an extensive review of the literature, the study compiles information from a variety of academic sources, including encyclopedias, scholarly journals, and reputable reports that can be accessed via online databases like Web of Science, Google Scholar, yearbooks, World Bank publications, UN Organization's databases, the UN Digital Library, and JSTOR.

This thesis intends to provide important insights into potential pathways for reducing water scarcity through the implementation of sustainable energy initiatives by shedding light on the important relationship between energy and water dynamics in arid and semi-arid regions through this logical examination.

Key words: Solar, Wind Energy, Sustainable Energy, Arid and Semi-arid Areas, Water

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List of the abbreviations used in the thesis

AC	Alternating Current
AI	Aridity Index
BSAR	Brazil's Semi-Arid Regions
CFD	Computational Fluid Dynamics
DC	Direct Current
DNI	Direct Normal Irradiance
ESP	Electrical Submersible Pump
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas Emissions
HPP	Hydroelectric Power Plant
HRES	Hybrid Renewable Energy System
LAC	Latin America and the Caribbean
LCC	Life Cycle Cost
MVC	Mechanical Vapor Compression
NGOs	Non-governmental Organizations
P	Precipitation
PET	Potential Evapotranspiration
PV	Photovoltaic
RO	Reverse Osmosis
TCO	Total Cost of Ownership
UNDP	The United Nations Development Programme
VFDs	Variable Frequency Drives
WEI	Water Exploitation Index
WTP	Water Turbine Pumps

1. Introduction

One of the biggest problems in dry and semi-arid areas of the world is a lack of water. Water resources are frequently scarce. It occurs especially in the less developed nations in Africa, Asia, and Latin America. The United Nations Sustainable Development 2030 Agenda set Sustainable Development Goal 6 ("Ensure availability and sustainable management of water and sanitation for all) and SDG 7 ("Ensure access to affordable, reliable, sustainable and modern energy for all) to create a sustainable environment.

This bachelor's thesis endeavors to comprehensively explore and evaluate solar and wind-driven water pump designs, with a particular focus on their applicability in selected countries across Africa, Asia, and Latin America. Specifically, the study centers on Cape Verde, Egypt, Morocco, South Africa, China, India, Pakistan, Brazil, Chile, and Mexico. The primary objective is to assess the feasibility and effectiveness of these water pump technologies within diverse socio-economic and environmental contexts across discussed regions.

To provide an in-depth evaluation, a SWOT analysis is conducted to identify the strengths, weaknesses, opportunities, and threats associated with the adoption of solar and wind-driven water pump technologies. These technologies bring obstacles as well, such as potential effects on wildlife and limited regional applicability, even while they declare benefits like decreased reliance on fossil fuels and enhanced environmental quality.

The thesis emphasizes the amount that additional investigation and debate about using renewable energy to power water pumps in arid and semi-arid regions needs to be done. There is an opportunity to improve water security for communities dealing with water scarcity issues around the world and promote sustainable development by utilizing the unique attributes and benefits of these technologies.

2. Aims of the Thesis

This thesis endeavors to comprehensively explore and evaluate solar and wind-driven water pump designs, with a focus on their applicability in the arid and semi-arid regions of Africa (Cape Verde, Egypt, Morocco, South Africa), Asia (China, India, Pakistan), and Latin America (Brazil, Chile, Mexico). The primary objective is to assess the feasibility and effectiveness of these water pump technologies across diverse countries within these regions. This evaluation encompasses a thorough consideration of environmental factors, technological feasibility, economic viability, and potential socio-economic impacts on local communities. By conducting in-depth research and analysis, this thesis aims to advance the understanding of renewable energy-driven water pump systems and their potential to mitigate water access challenges in arid and semi-arid regions in the three continents described.

3. Methodology

The methodology adopted in this thesis employs a comprehensive approach to investigate renewable energy-driven water pumping systems and their potential to mitigate water scarcity in arid and semi-arid regions.

The literature review entailed a thorough examination of scholarly articles, reports, and publications on renewable energy-driven water pumping systems, challenges of water scarcity, and sustainable development initiatives within these regions. Various online databases such as Web of Science, Google Scholar, Yearbooks, World Bank publications, UN databases, the UN Digital Library, and JSTOR were utilized to access pertinent literature. A systematic analysis of this literature was conducted to identify key concepts and emerging trends.

Empirical investigations involved case studies from Africa, Asia, and Latin America to gather data and insights. The collected data were analyzed and interpreted using SWOT analysis.

Subsequently, a comparative analysis was performed on different renewable energy-driven water pumping technologies, encompassing solar-powered and wind-powered systems.

4. Literature Review

4.1. The characteristics of arid and semi-arid regions

High climate volatility, social stress, water shortage, and resource instability are characteristics of many semi-arid locations. It takes integrated research involving climatology, hydrology, and socioeconomic studies to analyze dynamic natural conditions and evaluate potential mitigation measures for semi-arid regions against the current and changing climate (Simmers 2003).

Dry and semi-arid regions have been correlated with dry locations. They are characterized by little rain (arid regions receive less than 25 cm of rain annually whereas semi-arid regions get between 25 and 50 cm of rain per year) and significant evaporation conditions which often result in serious water scarcity and drought events. The aridity index (AI) represents the degree of climatic dryness and is defined as the ratio of annual precipitation (P) to annual potential evapotranspiration (PET). In the context of this AI system, drylands are delineated as areas characterized by an AI (Aridity Index) below 0.65. Within this classification, drylands are further categorized into hyper-arid regions ($AI < 0.05$), arid ($0.05 \leq AI < 0.2$), semi-arid ($0.2 \leq AI < 0.5$), and dry sub-humid ($0.5 \leq AI < 0.65$) subtypes (Middleton and Thomas 1997).

Desertification, a process when fertile land becomes increasingly drained and degraded because of factors like overgrazing, deforestation, and irresponsible agricultural methods, is another danger for those regions. In semi-arid regions, the implementation of water resource management must also overcome climatic variability (Krol et al., 2006).

Overall, arid, and semi-arid environments present significant barriers to agriculture resulting from a shortage of water sources and arable land.

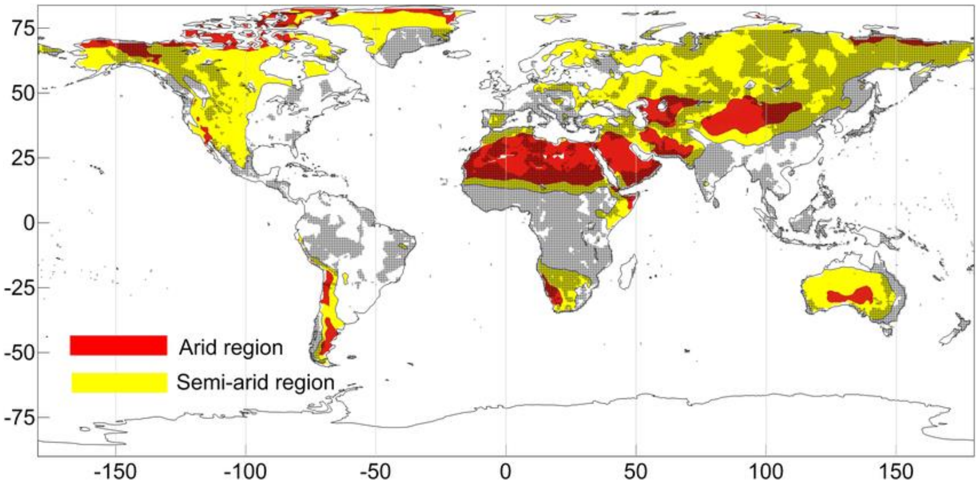

Figure 1 The location of arid and semi-arid regions

Source: Ma 2019

Water shortages in semi-arid areas worsen and endanger ecosystems, human health, and food production. Semi-arid regions of southern Africa, North and South America, and the northern Mediterranean are predicted to extend quickly. “The countries with the most severe development problems are those where climate affects access to water” (Morante-Carballo 2022).

The amount of vegetation in those areas is typically restricted and drought-tolerant plants (weeds, shrubs, succulents, etc.), and animals (hare, gazelle, camel, etc.). There are also major temperature swings in arid and semi-arid regions, with scorching days and cooler nights. Severe heat waves may also exacerbate the pressure on human population and ecosystems. A key feature of arid and semi-arid regions where access to sources of fresh water is difficult is water scarcity. A shortage of water may arise from groundwater reserves being utilized far quicker than they can be restored.

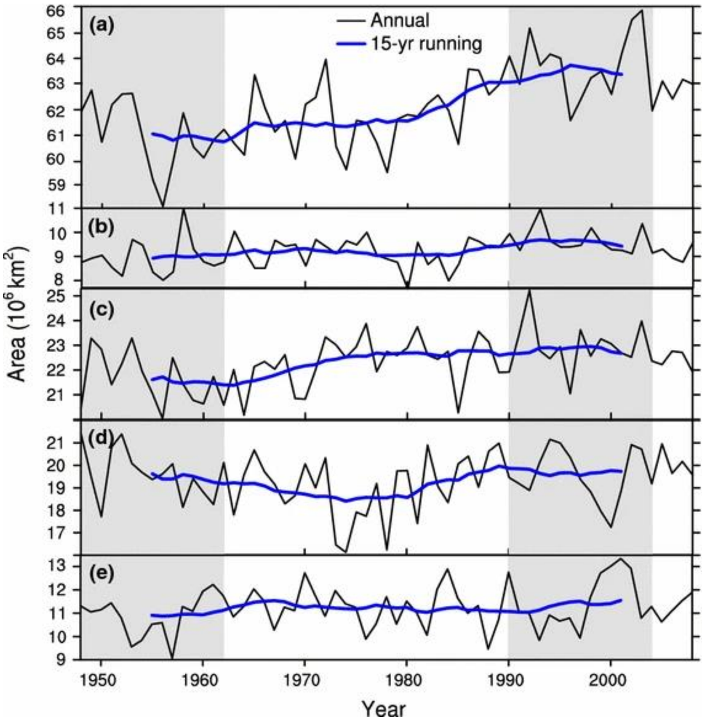

Figure 2 : Temporal variations in the arid and semi-arid areas over a half a century

Source: Huang et al. 2015

Temporal fluctuations in the area (measured in units of 106 km2) are examined for the entirety of drylands, as well as for sub-categories including dry sub-humid, semi-arid, arid, and hyper-arid regions, spanning the period from 1948 to 2008. A 15-year running mean (depicted by thick blue curves) is employed to accentuate trends in response to climate change.

The research team around Morante-Carballo (2022) created a Sankey diagram using the Biblioshiny library. It captures major topics in discovering water-related discourse divided into three phases, for in total of 54 years. First, it is only about water stress and groundwater. Then the water stress is examined in terms of stomach conductance, while groundwater research delves into issues of water scarcity. Subsequently, it adds more topics, such as irrigation, water shortage, growth, and water-use efficiency. In recent years, it has become the most specialized, also concentrating on soil moisture, evapotranspiration, or deficit irrigation.

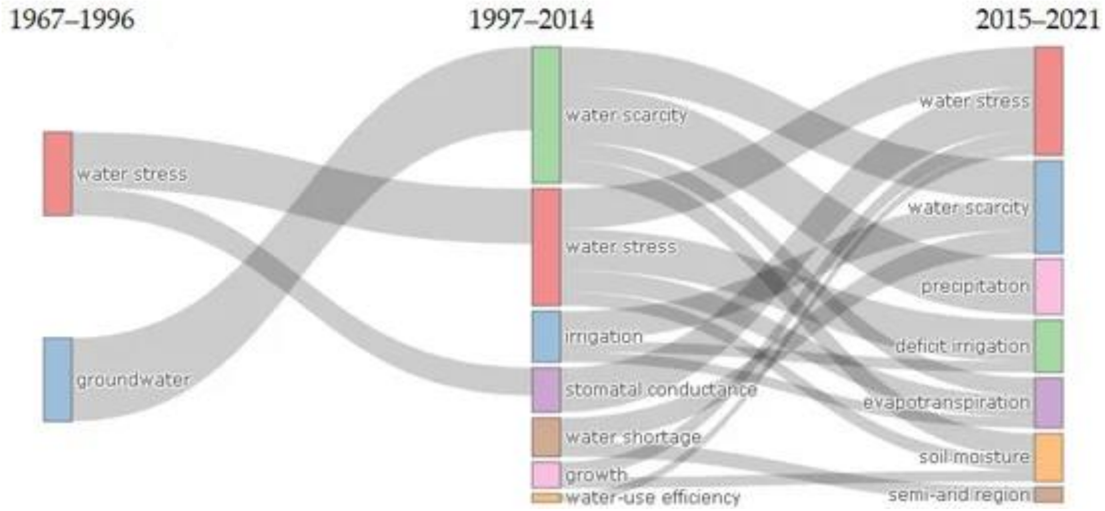

Figure 3 Sankey diagram visualizing evolution of water scarcity in semi-arid zones

Source: Morante-Carballo et al. 2022

Climate change is significantly impacting arid and semi-arid areas, leading to ecosystem degradation, biodiversity decline, and changes in species distribution and population size. Climate change has precipitated numerous challenges, including ongoing degradation of ecosystems and consequent declines in biodiversity. Furthermore, the warming climate induces various indirect consequences, altering vegetation patterns and sea levels, thereby impacting both physical and biological systems. Consequently, shifts in species distribution, population size reductions, and localized extinctions have ensued. The compounding effects of climate change alongside the proliferation of diseases, which intensify over time, contribute to the gradual disappearance of many species. These issues imperil various components of biodiversity, edging them perilously close to collapse (Boutaj 2022).

These changes are particularly pronounced in China, where the expansion of semi-arid regions has outpaced that of arid and sub-humid areas, and the greatest warming has been observed in these regions. The intensification of drier climates in these areas is also associated with the weakened East Asian summer monsoon (Huang 2019). These findings underscore the urgent need for effective climate change mitigation and adaptation strategies in arid and semi-arid regions.

4.2. Water consumption

Water is a fundamental necessity for the sustenance of all living organisms, including the human body. A body, weighing 70,55 kg consists of water 67,85% (for an adult may vary between 58 and 80%), the most is in the lungs, kidneys, and striated muscle (Mitchell et al. 1945) and the specimen's water and fat composition ought to serve as a reliable indicator of overall nutritional condition. Despite being given access to clean drinking water as a basic human right, many parts of the world lack infrastructure for a minimum-quality water supply or live in precarious conditions.

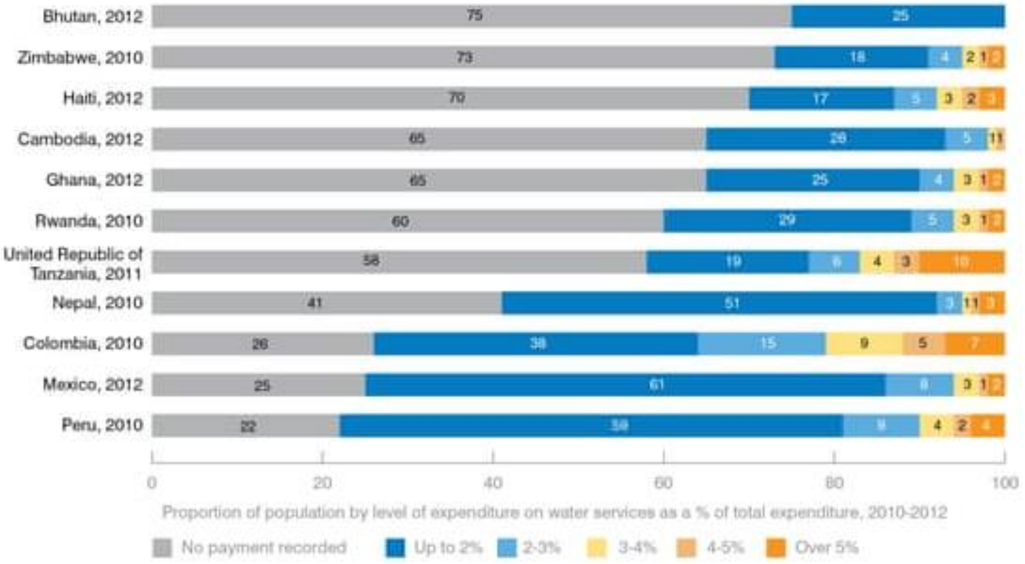

Figure 4 Proportion of population by level of expenditure on water services, in %

Source: WHO/Unicef Joint Monitoring Programme

Between 2010 and 2020, the number of people living in water-scarce places worldwide increased from 2.04 to 2.36 billion, and by 2030, it is predicted that this figure will have reached 2.70 billion (World Water, 2023).

Urban water supply systems face escalating strain due to rising population numbers, economic expansion, shifts in lifestyle patterns, and the progression of urbanization. The compounding effects of climate change exacerbate these challenges, intensifying issues of water scarcity and deterioration in water quality within urban areas. Developing and underdeveloped nations encounter heightened vulnerabilities stemming from resource constraints, rapid population growth, limited GDP, the presence of polluting industries, inadequate institutional responses, and deficiencies in planning and management practices (Talat 2021).

As we scrutinize the historical backdrop of water utilization, we cannot overlook Mesopotamia's influence which brought inventive methods for water resource management. A complex system of canals and waterworks was developed, with the dual function to ensure irrigation and to be used as waterways. In the region called the “fertile crescent” situated between the Tigris and Euphrates rivers, the earliest civilizations were born more than eight thousand years ago. Water technology extended beyond irrigation in Mesopotamia, where advancements in sanitary engineering were also pioneered. Numerous cities boasted extensive networks of wastewater and stormwater drainage systems. However, the excessive exploitation of land and water resources for agricultural purposes had adverse environmental impacts, leading to issues such as silting and soil salinization (Tamburrino 2011).

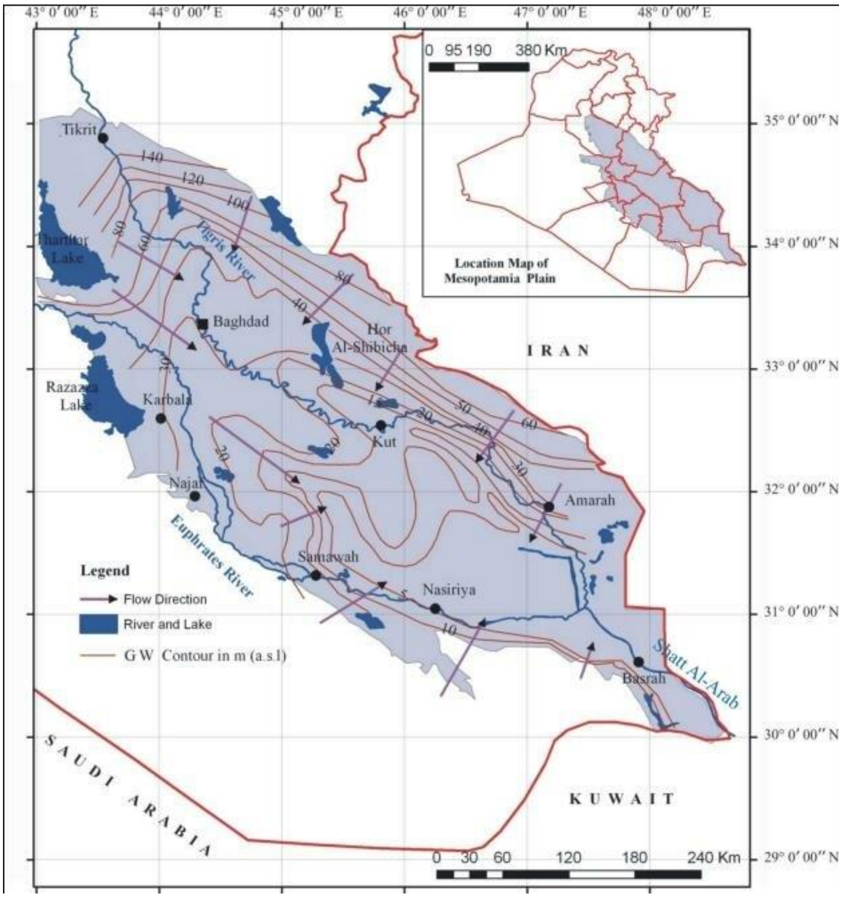

Figure 5 Static ground water level map with flow direction of the Mesopotamia Plain

Source: Al-Ansari et al. 2020

The livelihoods of individuals in developing nations primarily hinge upon natural resources such as water, soil, and pastures, rendering them susceptible to the impacts of climate change compared to their counterparts in developed nations. Water consumption in less developed countries is a critical issue, with access to household running water being significantly lower than in developed countries. Households in low-income nations exhibit disparities compared to those in high-income countries concerning average income, educational attainment, and possession of water-utilizing appliances. Additionally, they often confront distinct challenges related to accessing safe drinking water. For instance, households in low-income settings frequently encounter a range of options when selecting a source of potable water (water vendors, communal wells and pumps, private pipe but they all differ in the sense of quality, price, convenience, and/or reliability (Renzetti 2002).

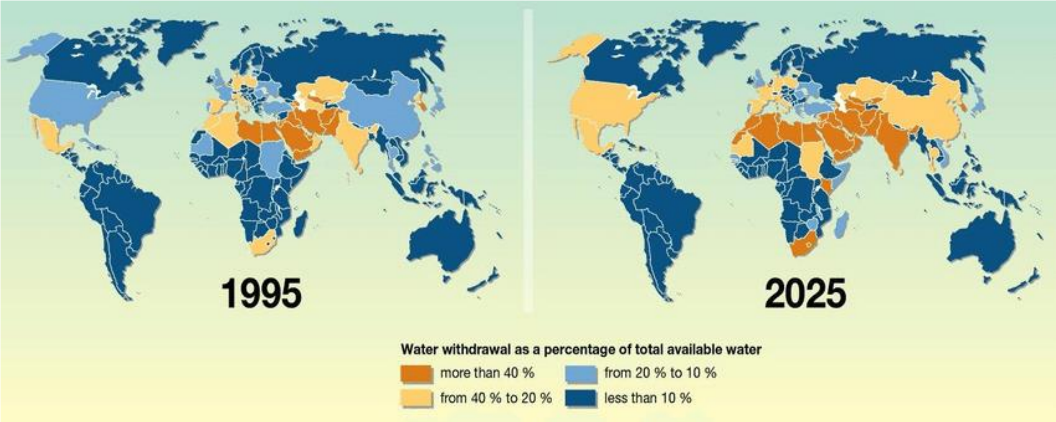

Figure 6 Worldwide water stresses map

Source: Nasr Bensalah 2011

Typically, 10% of the global populace resides in nations facing high or critical water stress, substantially impeding access to and availability of water for personal necessities. Water plays a pivotal role in disease prevention, including combating ailments such as the newly identified COVID-19, and its scarcity profoundly impacts economic endeavors, agricultural output, and consequently, food security. During periods of water stress, farmers may encounter escalating disparities in their access to water resources. Therefore, advocating for not only sustainable but also inclusive and integrated management and governance of diverse water sources becomes imperative (FAO & UN Water 2021).

Groundwater constitutes 29.9% of total freshwater resources, with lakes, rivers, and reservoirs collectively accounting for a mere 0.26%. Soil moisture contributes 0.94% to the freshwater inventory. Direct human consumption primarily relies on groundwater, which comprises 96.80% of accessible water, with river water constituting a minimal 0.02% and lakes accounting for 3.18%. Nonconventional water sources include desalinated water and treated wastewater (Alsharhan et al. 2020).

The strain on renewable freshwater reserves is quantified through the Water Exploitation Index (WEI), calculated as the disparity between water abstractions and water replenishment, divided by the renewable water resources within a specified geographic area. Seasonally, notable disparities in the WEI are evident across numerous countries. Even in regions not typically regarded as prone to water scarcity, water deficits are observed, as seen in the case of north-western Germany, eastern Poland, northern-eastern France, and Belgium (Preisner 2022).

Some of the solutions to a more sustainable water treatment might be to efficiently use water, accurately detect water stress, utilize water sources for supply, and treat wastewater recycling for irrigation. Biodiversity exhibits resilience in the face of climate change through the evolution of adaptive systems that facilitate survival and the preservation of species and ecosystems. These mechanisms encompass biological, ecological, and evolutionary responses that enable organisms to withstand environmental pressures and maintain ecological balance. Through genetic diversity, species possess the capacity to adapt to changing climatic conditions, ensuring their persistence over time. Also, conservation efforts play a pivotal role in safeguarding vulnerable species and habitats, thereby bolstering biodiversity's ability to mitigate the adverse impacts of climate change. By fostering resilience, biodiversity serves as a critical buffer against the deleterious effects of climate change, contributing to the long-term sustainability of ecosystems and the broader biosphere (Boutaj 2022).

The substantial increase in global water usage over the past five decades has elevated its prominence on the agendas of numerous organizations. With household access to running water remaining limited, public standpipes have emerged as crucial water sources for impoverished households (Gaye, 2003).

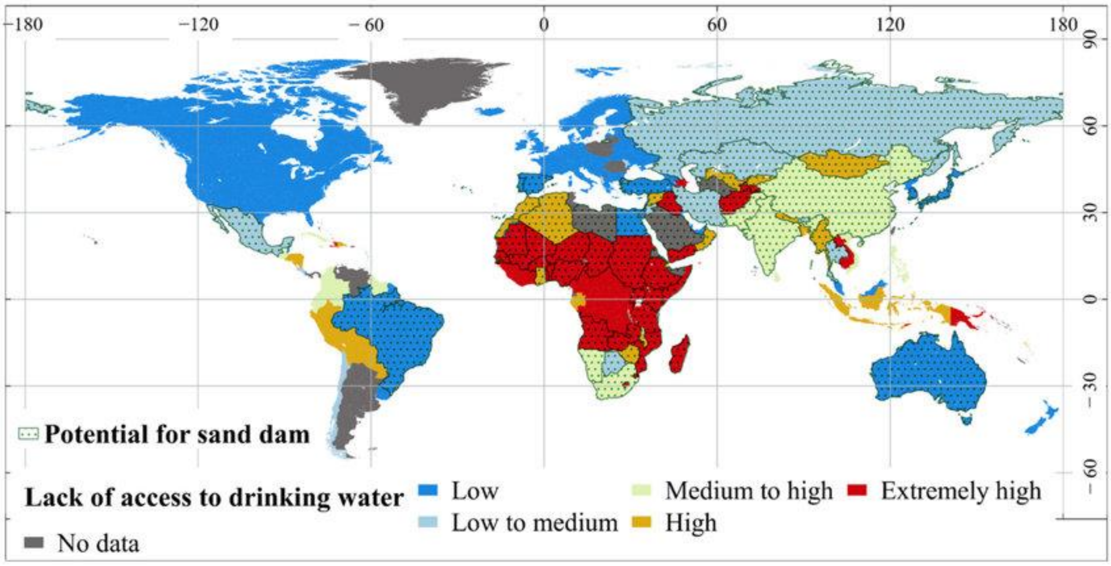

Figure 7 Lack of Access to Drinking Water

Source: Yifru et al. 2021

This scarcity is further exacerbated by the fact that these countries often rely heavily on water for consumption needs, with some using up to 100% of available water. Water utilization patterns vary across global regions, predominantly influenced by agricultural, industrial, energy, mining, service, and municipal supply demands. Developed nations typically allocate less than 5% of water for household consumption, prioritizing drinking, and cooking needs, whereas some developing countries allocate virtually their entire water supply towards consumption requirements (Preisner, 2022).

Water shortage comes in two forms: economic and physical. The term "physical water scarcity" describes an abundance of water brought on by weather patterns, climate change, and droughts. On the contrary, institutional shortcomings such as inadequate planning, low investment, and inadequate infrastructure are the cause of economic scarcity (Genesis Water Tech 2023).

In the Millennium Declaration of the UN General Assembly in 2000 a commitment was made to halve by 2015 the global proportion of people without access to safe drinking water. Measurement of water availability per capita (WPC) constitutes a fundamental aspect in the realm of water resource management. WPC is the total quantity of water accessible to each individual in a given location. It is commonly stated on a daily, monthly, or annual basis and is usually quantified in terms of volume, such as liters or cubic meters. It is a crucial indicator of the availability of water and varies greatly based on several variables (location, climate, population density, water infrastructure, water management technique). WPC tends to be high in areas with plenty of freshwater resources and low population density and may be lower in water-stressed or heavily populated areas. Generally, the amount of water consumed per person rises as income does. Chenoweth (2008) proposed a minimum per capita fresh water requirement of 135 liters per person per day for human health and economic and social development.

A study that investigated the impact of household features on per-capita water use (Hussien et al. 2016) in Duhok City in Iraqi Kurdistan revealed that an “increased number of children in the household leads to a higher reduction in per capita consumption than elders [...] increased number of male adults in the household reduces per capita consumption and the increase in female members increases per capita consumption“. Over the period from 1970 to 2014, rapid population growth resulted in a decline in per capita water availability from 12,900 m3 to 5926 m3. Key global water challenges include uneven distribution, water quality deterioration, escalating demand, and the impacts of climate change (Alsharhan et al. 2020).

The water used for the production of items we use every day such as cotton, paper, our clothes, etc., amounts to 167 liters daily and the water consumed to produce our food amounts to 3,496 liters a day per person (WHO). The significance of water availability as a vital resource essential for sustaining life on Earth is anticipated to increase in the forthcoming decades. The critical inquiry pertains to the duration during which the water ecosystem can endure anthropogenic pressures, and when intervention might be necessary to preserve crucial freshwater resources for humanity's most essential needs (Preisner 2022).

AQUASTAT, the FAO's global information system on water and agriculture, has played a significant role in contributing to the World Water Development Report since its launch in 1993. It provides extensive data and analysis on water resources and agriculture worldwide, offering a variety of resources such as online data by country, digital geographical data on irrigation and water resources, and specific studies covering topics like world water resources, irrigation potential in Africa, and projections of future agricultural water use. This comprehensive system serves as a valuable resource for agricultural water management, offering detailed information on water resources and irrigation practices (Eliasson, 2003).

There is also a measure to assess the scarcity of freshwater resources, the Water Stress Index which quantifies the ratio of water withdrawals to renewable water resources in the region. It is calculated by dividing the total water withdrawals by the total renewable water resources available in the area. This ratio provides insight into the level of stress on water resources: below 20% indicates low water stress, between 20% and 40% indicates moderate water stress, and above 40% indicates high water stress, which leads to depletion of water sources.

4.3. Pumps

4.3.1. History of the pumps

The inception of wind energy as a viable resource can be traced back to the Middle Ages, wherein its utilization primarily entailed water pumping, marking the genesis of its adoption.

Throughout history, the Dutch have utilized wind energy to reclaim land, particularly within areas safeguarded by dikes, allowing for territorial expansion from the sea. Other documented cases include using wind power to irrigate potato fields on the Cretan Plateau of Lassithi and to provide water for livestock on farms across the American Midwest. In modern times, the adoption of small-scale wind-electric systems for water pumping has gained traction due to their increased flexibility compared to mechanical alternatives and the added advantage of being able to utilize surplus electricity for various purposes (Velasco et al. 2004).

Ancient civilizations, including the Greeks, Romans, and Egyptians, utilized a variety of water supply techniques, such as aqueducts, cisterns, and wells, to meet the needs of their urban centers. Urban hydraulic systems began to emerge in a region spanning from India to Egypt during the Bronze Age, and more specifically at the middle of the third millennium BC. Advanced urban water technologies were created in Greece, especially on the island of Crete. These included the building and usage of cisterns, aqueducts, wells, fountains, restrooms, and other sanitary facilities, all of which imply a lifestyle similar to the one presently (Mays, 2007).

The Arabs in southern Spain also employed innovative methods, such as contour-hugging open channels, to transfer snowmelt and sustain spring flows (Headworth, 2004).

Because these pipes were made to line the land's natural contours, agricultural fields could be effectively and efficiently irrigated. The channels were able to capture and transport water more equally throughout the terrain by adhering to the contours, which prevented erosion and made sure that water reached crops in a controlled way.

Greek inventor Hero of Alexandria invented a wind-powered organ with a wind wheel in the first century. This machine powered a piston and forced air out of pipes. Originally, mill machinery powered by a water wheel or windmill used wheel and crank reciprocating models to operate the first industrial firewater pumps. Early firewater pumping systems, including waterwheels and reciprocating pumps, were developed by civilizations for agricultural irrigation and fire extinguishment. Considering the most practical type of pump, modern centrifugal water pumps work at speeds considerably greater than those that were easily attainable prior to the invention of steam or internal combustion engines and electrical motors (Nolan, 2011).

In Australia, early water pumping technology, including steam-powered pump sets, played a crucial role in the supply of water for mining and pastoral stations. Although wind power was available, landowners keen to capitalize on their lands bought English steam technology from the 1830s, which was adapted for the Australian climate. These pump sets were significant installations in and of themselves, and they remained in use until the 1890s when oil motors were introduced (Ridgway, 2008).

In 1854 Daniel Halladay in Connecticut invented and patented the first autonomous windmill that was used in the U.S. for over a century. The Halladay wind machine plant moved to Illinois in 1863, to be nearer to the expanding windmill market in the Midwest and Great Plains, North America (Wishart 2011).

Figure 8 Windmill

Source: J. O. Walker Collection 2010

It was the first successful self-regulating windmill which became known as the "Halladay windmill" and it transformed the use of wind energy for rural water pumping. Halladay created an innovative self-regulating windmill including four solid blades affixed to a main shaft and a fixed vane. “The rigid vane kept the wheel of blades facing the wind at an angle to produce the greatest amount of power. As wind velocities increased and the wheel spun faster, a centrifugal governor changed the pitch of the blades to present less of their surface to the wind, thus controlling their speed” (n. d.). Windmills continued to be significant features of the landscape in the Great Plains. Throughout most counties in the region, individuals known as "windmillers" persist in their trade of setting up and maintaining these structures. Windmills are still produced by manufacturers located both within and outside of the Great Plains, ensuring their availability for those in need of them (Wishart, 2011).

Wind turbines were commonly employed for generating modest quantities of electricity to operate lighting, tools, and appliances. The utilization of hydraulic mechanisms traces its origins to ancient civilizations, dating back to approximately 3,000 BCE with the first known use by the ancient Egyptians for agricultural irrigation (Nolan 2011). These early hydraulic systems, exemplified by the shadoof utilized by ancient Egyptians, represented rudimentary yet vital tools for tasks such as irrigation and water elevation.

Advancements in hydraulic technology persisted through ancient Greece and Rome, witnessing the development of intricate aqueduct systems that incorporated a variety of water-lifting devices. The advent of the Industrial Revolution in the 18th and 19th centuries marked a transformative period for hydraulic engineering, driven by the widespread adoption of steam-powered engines. This era witnessed significant innovations, including the introduction of the centrifugal pump by Denis Papin, which revolutionized water transfer methods and facilitated the establishment of expansive water distribution networks. The pumps have played a crucial role in the development of water engineering and have been continuously improved to meet the needs of different civilizations (Yannopoulos 2015).

In the contemporary era, hydraulic systems continue to play a pivotal role across diverse sectors, encompassing agriculture, municipal water supply, wastewater management, and industrial processes. The ongoing evolution of hydraulic technologies, characterized by diverse designs and technological innovations, serves to enhance sustainability in water management practices, thereby addressing the pressing challenges of global water scarcity.

4.3.2. The importance of sustainable and renewable energy-driven water pump systems

Like other industries, agriculture is becoming more and more dependent on energy, especially for more sophisticated methods like irrigation. Water shortage is a problem in arid and semi-arid areas, and it is made worse by variables like population growth and climate unpredictability. Many still depend on seasonal rains for pumping, despite efforts to obtain modern energy. Traditional fuel-based pumps can be difficult to maintain and find, particularly in rural locations. On the other hand, wind and solar energy are beneficial in these areas and have limitless availability. Stressing the importance of energy efficiency is essential for both cost savings and environmental protection (Isaías et al. 2019).

Renewable energy systems, notably solar and wind-driven pumps, are progressively pertinent in arid and semi-arid locales for irrigation purposes. In rural areas where connection to the electrical grid can be problematic but renewable energy resources based on solar and/or wind power are numerous, the usage of autonomous water pumping and desalination equipment powered by renewable energy sources can be a workable alternative. Their primary characteristic is the intermittent produced electricity that is "given" or offered according to the solar radiation and wind speed (Xavier et al. 2012). These autonomous systems with sporadic input power are more common in contemporary systems, such as smart grids and renewable energy systems.

New government regulations are attempting to include renewable energy sources, mostly in wealthy nations (Ramos 2009). The importance of sustainable and renewable energy-driven water pump systems lies in the ability to minimize energy use and environmental effects emphasizes it.

Hydro-powered pumps, in particular, are highlighted as a cost-effective and environmentally sound alternative (Zambrano, 2019). In comparison with their diesel- or electric-powered equivalents, they tend to be more affordable.

A range of water pumping systems have been developed for various applications. Colt (2006) evaluated the performance of different types of marine aquaculture pumping systems, including pier mounted, package, submersible, float mounted, and tidal cycle pumps. According to his research, high tidal pumping and floating pump stations are attractive options for various sites, especially in laboratories with extreme tidal ranges or fluctuating seawater quality, and in shrimp aquaculture due to reduced pumping needs. However, they require larger equipment, sophisticated monitoring systems, and storage for non-pumping periods.

Alternative sources of energy like solar photovoltaic and wind power are becoming more accessible for water-pumping applications, which lowers GHG emissions. This is a result of recent advancements in power electronics and motors. Because of its many benefits, studies on alternating current motor-based water pumping systems (WPS) have gotten lots of interest recently (Angadi 2021).

Thirty pressure-based hydroelectric pumping methods have been categorized and displayed in location and time globally. “Despite the lack of discernible patterns, certain notable clusters can be found in areas like Europe, South-Southeast Asia, and Eastern Africa […], and yet each of them has shown to be a good substitute for traditional pumping methods, which can be overly costly or difficult to get, especially in isolated and rural areas” (Zambrano, 2019).

4.3.3. Water pumps

Water turbine pumps (WTP) are extremely demanding in supplementary civil works, in contrast to other ready-to-use Hydroelectric Power Plant (HPP) devices. They usually need pits to house the machine and dams, weirs, and/or gates to produce artificial drops, increasing the operating head.

The first type of water turbine, known as a waterwheel, was more often utilized in the distant past. Other types of water turbines include crossflow, axial, mixed, and tangential flow, as well as pumps that operate in reverse and are commonly referred to as pump-as-turbines. The best water pumping system should be chosen after taking into account several aspects like the water supply, flow rate, head, cost, energy availability, and environmental impact.

Advantages of hydro-powered pumps

One of the most beneficial solutions to the problem of improving the quality of life and providing remote rural populations with the benefits of electrification and related advancement is micro-hydropower. In nations with fewer resources, it is among the most affordable energy solutions for electrifying rural areas (Jain 2014). Hydro-powered pumps offer several advantages, making them a viable alternative to conventional pumping technologies. They are environmentally friendly, cost-effective, and particularly beneficial in remote or off-grid areas (Zambrano, 2019).

Hydro-powered pumps have the potential for significant energy efficiency, particularly when incorporating contemporary innovations like variable frequency drives (VFDs) and streamlined system configurations. While they may have lower efficiency, this can be mitigated by optimizing their dimensions (Obsieger, 2002). In small-scale hydroelectric power systems, pumps can be used in turbine mode, providing a low-cost and versatile solution (Jain, 2014). Additionally, the use of hydraulic air pumps in low-head hydropower systems can significantly increase turbine-generator speed and reduce maintenance costs (Howey Pullen 2009).

In comparison to conventional fossil fuel-powered pumps, hydro-powered pumps emit minimal greenhouse gases and pollutants, thereby aiding in the reduction of carbon footprints and the amelioration of climate change, positioning them as environmentally advantageous alternatives.

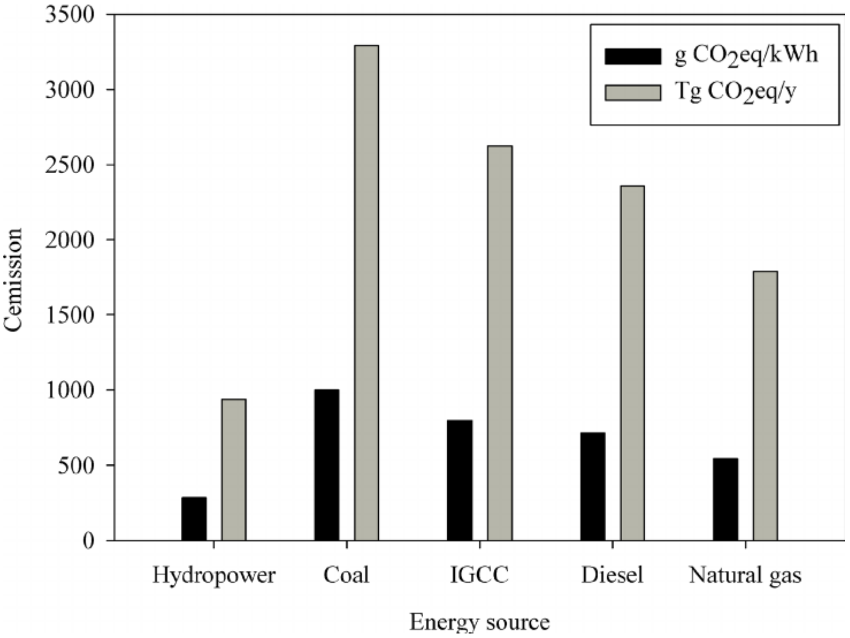

Figure 9 Comparison of carbon emission between hydropower and fossil fuel alternatives (3,288 TWh for hydroelectricity is considered)

Source: Google

Disadvantages of hydro-powered pumps

Hydro-powered pumps, while offering potential cost savings and design flexibility, have several disadvantages. These include the need for efficient control systems to manage dynamic behavior and shut-off (Borga, 2002), and the influence of discharge demand on energy production in water supply systems (Ramos, 2000). Hydro-powered pump projects carry notable social and cultural implications for local communities, encompassing alterations in traditional land use practices, considerations for cultural heritage preservation, and impacts on community cohesion.

Although hydro-powered pumps inherently produce minimal emissions, the implementation of large-scale hydroelectric projects can result in considerable environmental consequences. Such projects typically necessitate the construction of dams and reservoirs, actions that can disturb natural river ecosystems, modify water flow dynamics, and impact aquatic habitats. Moreover, these endeavors may contribute to habitat degradation and sedimentation processes.

There is a notable lack of attention or adoption of hydro-powered pumps in contemporary contexts. It implies the presence of potential challenges or limitations inherent in hydro-powered pump technology, encompassing aspects such as cost, accessibility, technological constraints, or competition from alternative solutions. The unconventional use of pumps as turbines, while offering easy implementation and cost savings, may not be suitable for all water systems due to these limitations (Ramos, 1999).

4.3.4. Wind-powered water pumps

Since it emits no greenhouse gases or hazardous pollutants, using the wind to generate electricity is one of the greenest and most sustainable methods of producing energy. There are numerous impacts of wind power generation, such as on the environment. Wind turbines placed on flat areas need the use of more land than those in hilly terrain (Google). They must be spaced approximately 5 to 10 rotor diameters (the diameter of the circle's cross-section that a wind-powered energy generator sweeps) apart.

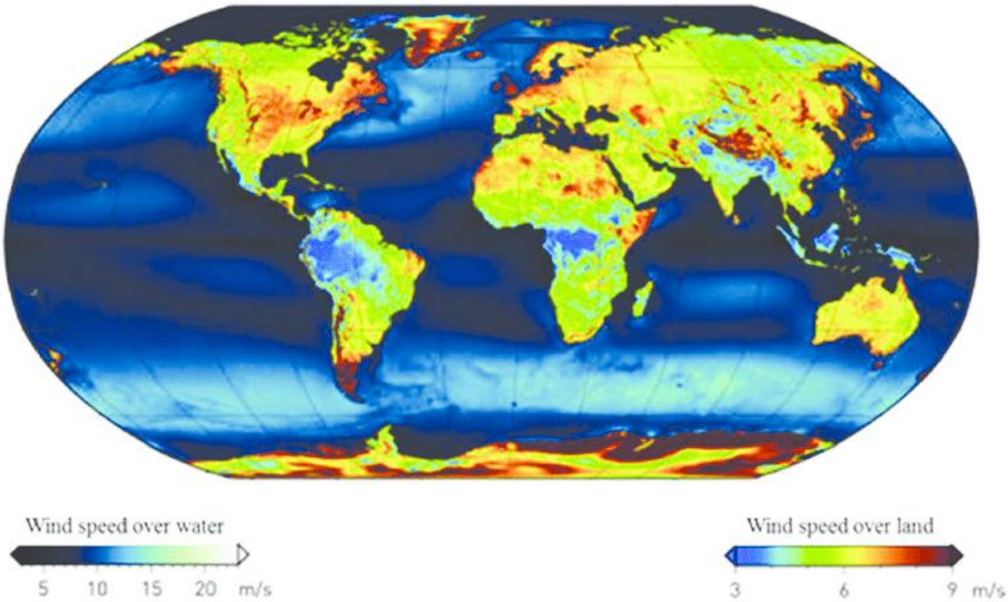

Figure 10 Worldwide average wind speed map

Source: Malek et al. 2016

Suleimani (2000) and Vosper (1985) both highlight the potential of wind energy in remote locations, with Suleimani specifically discussing the installation of a wind-powered electric water-pumping system in Oman and finding out that in isolated areas with sufficient wind energy resources, groundwater abstraction can be accomplished with success using wind energy. Also, his team understood booster pumps that circulate stored water during low wind periods might be powered by the wind turbine's excess energy, the water could be pumped to an above storage facility where gravity would provide it (Suleimani Rao 2000). Wind turbines are being built to function at ideal steady-state circumstances. But even so, successful start-up depends on the wind turbine accumulating enough kinetic energy before it gets connected to its load (Velasco et al. 2004).

Using reinforced fiberglass piping for subterranean firewater mains and specialized fire-rated fiberglass materials for all firewater piping on offshore structures is the newest trend in industrial facilities (Nolan, 2011). For many reasons, especially fire safety specialized infrastructure is needed for offshore wind farms.

The design of the wind-driven water-pumping system consists of key information of the system, such as the wind velocity measured in m/s and wind availability (for a certain speed range) in percentages. There are other formulas discussed when designing the system, such as wind speed data at a certain height above the ground, the total height of the turbine tower, and the head (the sum of the total height of the static water lift and of a combined friction and discharge pressure), derating for turbulence, and of course the water requirement on a daily basis (Suleimani Rao 2000). Using all the criteria mentioned, a proper wind electric water-pumping system can be chosen.

The aerodynamic force on the rotor blades of a wind turbine is the source of the mechanical loading on its parts (the shaft and blades) which results in changes in the mechanical loading, or wear and tear loading.

Storage devices, for example, flywheels, ultracapacitors, accumulators, or H2/O2 storage, are typically employed and scaled precisely to separate the power requirements for loads from the generation of intermittent power. However, their total cost of ownership (TCO) can be high because of their investment and lifespan, therefore reducing or even eliminating storage devices is a problem (Xavier et al. 2012).

In arid and semi-arid regions characterized by limited water resources, wind-driven water pump designs that demonstrate efficiency and reliability in low-wind conditions hold significant importance. I will only elaborate on three designs that are most suitable for the conditions prevalent in arid and semi-arid regions.

1. **Traditional Windmill Pump** commonly includes components such as a wind rotor, driving mechanism, compressor, storage tanks for both air and water, as well as pipes for conveying water and air pressure (Deo 2020). It harnesses wind energy to grind wheat or corn. It features a wheel with sails or vanes that are propelled by the wind, rotating a connected shaft. This shaft drives equipment for grinding or pumping water. In locations needing constant power or situated in river valleys, water wheels were often preferred. These windmill pumps are particularly beneficial in rural areas, where they can be built using locally available materials and skills (Maharasan, 2017).

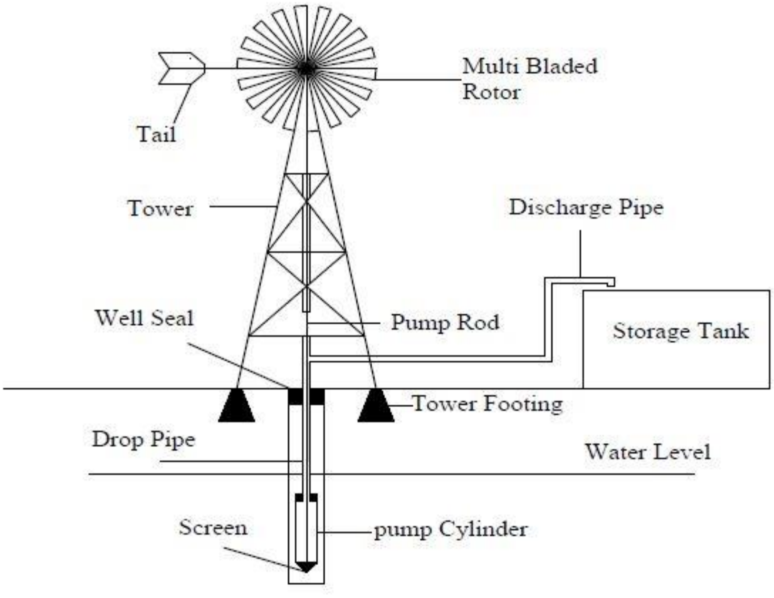

Figure 11 Windmill pump

Source: Len Calderone 2018

2. **Savonius Rotor Pump** is a vertical axis wind machine with high starting torque, making it suitable for standalone power generation and water pumping applications (Golecha, 2012). In water applications, the rotor's efficiency can be enhanced through novel blade shapes (Mosbahi, 2021). This design is optimal for decentralized water pumping applications, offering a dependable water supply in remote or off-grid areas characterized by restricted wind resources.

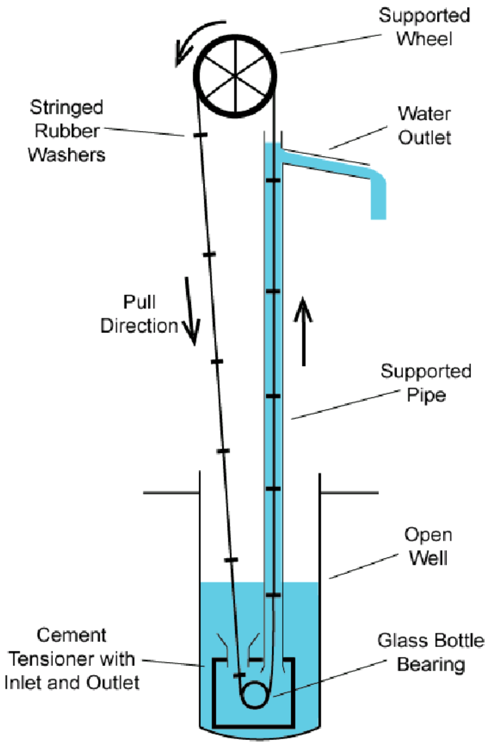

Figure 12 Savonius rotor pump

Source: Zingman 2007

3. **Solar-Wind Hybrid Pump**:

The solar panel harnesses sunlight to produce energy, which is then stored in a rechargeable battery. Similarly, the wind turbine generates energy, storing it in a rechargeable battery as direct current (DC) power. To match the requirements of the water pump motor, the DC power is converted into alternating current (AC) power using an inverter. A regulated power supply ensures that the circuit receives the necessary voltage to operate. This system is capable of functioning during the day, at night, or both. By amalgamating wind turbines and photovoltaic panels, it can effectively function in regions where wind resources are constrained (Srikanth et al. 2020), although the more hybrid it is, it is thought it would be more costly and with tendencies to it being more defective, as well.

The following graphic visualizes the conceptual design of a typical hybrid renewable energy system (HRES) in which pumped hydro storage is being used as an energy storage system. There are three energy sources noted – water, wind and solar. HRES, which has a mechanism for handling excess electricity, can be a separate electricity-producing system or connected to the main power plant. It can effectively use rainfall to generate electricity. Rainwater can be collected in the higher reservoir and then let to run downhill to turn the rotor of the hydro turbine, which generates electricity. The water is gathered in the lower reservoir and subsequently pumped back (Sajid & Choon-Man 2020).

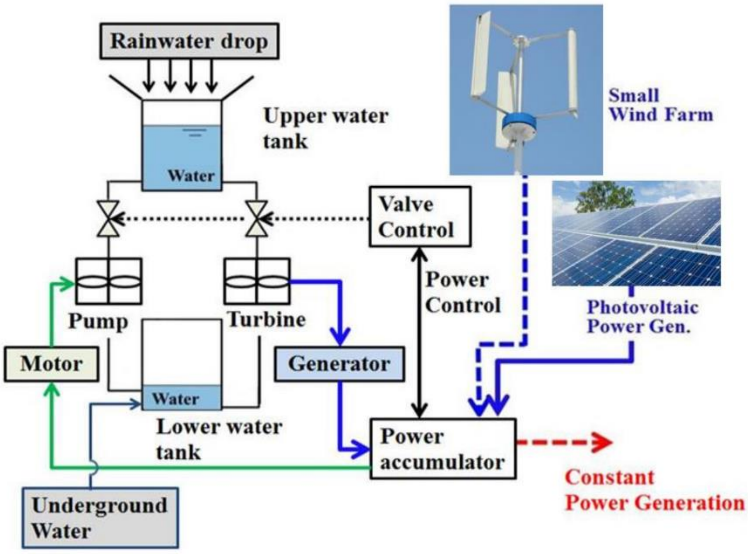

Figure 13 The design of hybrid renewable energy system for sustainable energy supply

Source: Sajid & Choon-Man 2020

In arid and semi-arid regions, wind-powered systems encounter several challenges due to the unique environmental conditions present, for example:

- lower wind speeds which reduce the potential energy output of wind turbines, impacting the overall efficiency of wind-powered systems,
- arid and semi-arid environments are prone to dust storms and sand accumulation, which can damage turbine blades and other components of wind-powered systems,
- wide temperature variations can affect the performance and longevity of wind turbine components, leading to increased maintenance
- limited water resources essential for the construction and maintenance of wind-powered systems, it increases the cost of implementing and operating wind energy projects in these regions,
- remote and inaccessible locations which makes it difficult to transport and install wind turbines and other infrastructure.

4.3.4.1. Building a wind-powered water pump

Residents of remote and rural locations have a sustainable solution in wind-powered water pumps. To capture wind energy and transform it into functional water pump power, every element is necessary.

The rotor assembly catches the kinetic energy of the wind with the blades attached to a central hub. Following that, the rotor shaft receives this energy, and the transformation process starts.

The rotor shaft could propel the water pump mechanism effectively because of its greater rotational speed provided by the gearbox and transmission system. This important step maximizes the efficiency of wind power generation by ensuring that energy is smoothly transported from the rotor to the pump. As a result of the way they are resistant to wear, hardened alloys or stainless steel are utilized. “This comprehensive approach ensures water availability and promotes sustainability, allowing communities to thrive under challenging conditions” (Ateya 2024).

4.3.4.2. Hi-Tech Water Transport: Exploring Contemporary Technologies

There are different water pumping systems to extract and distribute water, for different purposes (drinking water supply, agriculture, wastewater management, industrial processes):

- Centrifugal pumps are suitable for pumping water which makes them the most used in industry. They transform rotational energy into fluid energy (Desai, 2011). They come in a variety of forms and the distinctions in their construction are attributed to the size and turbidity of the pushed water (Scupi 2023). Their frequent use in cardiac mechanical support surgery carries some risks, which can be reduced with better surgical methods (Curtis, 1999).

However, with time, their effectiveness may decline, resulting in higher energy usage. “A typical company in South Africa using Centrifugal Pumps to supply water is the Rand Water […] pumping about 4.7 billion liters of drinking water from their booster stations per day through centrifugal pumps (Matiane, 2021). There are three types of centrifugal pumps - Radial flow pumps (The handled fluid travels radially out from the impeller), mixed flow pumps (uses a combination of radial and axial pumping motion to release fluid in a conical direction), and less used axial flow pumps (made from a pipe with a propeller inside).

- Submersible (floating) pumps, for example, Electrical Submersible Pump (ESP) is one type of artificial lift system widely used in oil wells owned by companies. They are essential for extracting fluids from wellbores in the oil and gas sector (Nguyen, 2020) as the liquid may be pumped from a mark up to minus thirty meters using these pumps. Additionally, they are utilized in water disposal and firefighting apparatus (Олеменов, 2021). They are especially useful in the oil business for extracting oil products from wells (Al-Obaidi, 2020). Artificial lift systems, which are necessary for long-term run-life enhancement in oil fields, depend mostly on this type of pump. Currently overseeing over 800 ESP systems spread throughout the North and South fields, Petroleum Development Oman plans to raise this number by 50% over the next five years (Al-Bimani, 2008).
- Jet Pumps work by using a high-pressure fluid jet (pressurized air or water) to force water to the surface after it has been drawn upward through a suction pipe. They are machines that draw water up from wells or reservoirs using a combination of suction and pressure which is why they are commonly used by domestic water supply systems and shallow wells; employed in many different applications: in hydraulic systems (Zhu, 2011), aircraft thermal management systems (Sherif, 2000), and the transportation of aggressive or hazardous substances, contaminated materials like solid particles, and food (Lisowski, 2010). Jet pump flow and performance have been modeled and examined using Computational Fluid Dynamics (CFD), which has yielded insightful information for the design and improvement of these pumps.
- Diaphragm pumps alternately expand and compress a chamber for carrying water using a flexible membrane to generate a vacuum, then the fluid is forced out of the pump under pressure. When air in an air chamber is moved in one direction, it compresses the air and draws liquid into the reservoir. When the air is moved in another direction, it flows into the reservoir, mixes with the liquid, and is released

as foam. This design is appropriate for a variety of applications as it can handle viscous, abrasive, and shear-sensitive fluids (Pelfrey 2012). A pivot element connected to the diaphragm and an electromagnetic drive are two ways to operate the diaphragm pump (Bittner 2007).

4.3.5. Solar-powered water pumps

We recognize two nonrenewable sources of energy:

- nuclear fuels (thorium and uranium)
- fossil fuels (natural gas, oil, and coal), each of which imposes a finite impact on the planet.

Various primary energy sources exist, including solar radiation, geothermal heat, Earth's rotation to the moon, and the gravitational pull of the sun's planetary system. Among these, only one source can be found on Earth in a diverse array of manifestations, hence the collective term "renewable energies." Solar energy exemplifies this renewable energy source, exhibiting widespread availability and diverse utilization potential. It can be captured through a variety of technologies, such as photovoltaic panels for electricity generation, solar thermal systems for heating and cooling, and passive solar design for architectural applications. Furthermore, solar energy drives numerous natural phenomena on Earth, including photosynthesis and weather patterns, rendering it a versatile and universally accessible renewable energy resource.

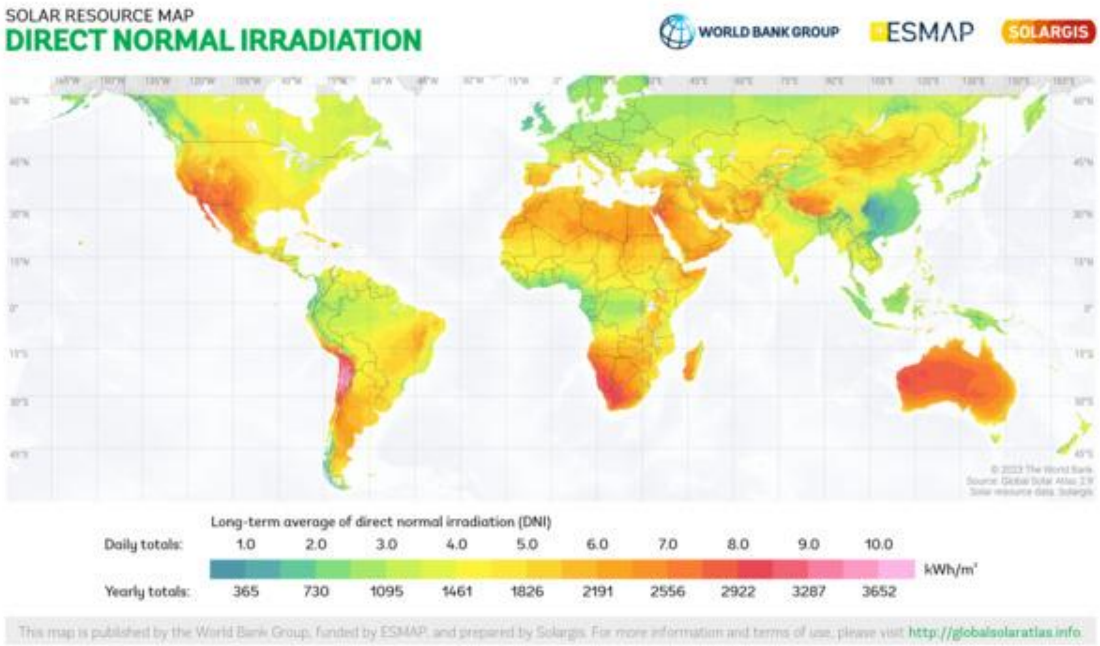

Figure 14 Direct Normal Irradiation

Source: Solargis 2020

The term "DNI" refers to the quantity of solar radiation that a surface, which is always held perpendicular to the direction of the rays of beams, receives per unit area. It stands for the portion of solar radiation that reaches Earth directly from the sun, unaffected by atmospheric reflection or scattering. In simpler terms, DNI measures the intensity of solar radiation that reaches a surface facing directly toward the sun.

Watts per square meter (W/m2) is the standard unit of measurement for DNI values, which could differ based on the hour of day, season, latitude, altitude, and air conditions. For optimal efficiency and performance, solar energy systems must be designed and optimized with accurate measurement and understanding of DNI.

The design of the solar-powered water-pumping system

Although photovoltaic (PV) systems often need a large initial investment, their numerous advantages make them a desirable substitute for traditional water pumping power sources. Because it emits no carbon dioxide, makes no noise, and requires little upkeep or operation, it is considered clean (Aliyu at al. 2018).

Solar-powered systems find application in diverse sectors. Photovoltaic systems consisting of one or more solar panels installed on residential rooftops generate electricity to power homes and reduce reliance on electricity. Some of them can even cover artificial light to electricity. “The first practical PV cell was developed in 1954 by Bell Telephone researchers” (Google).

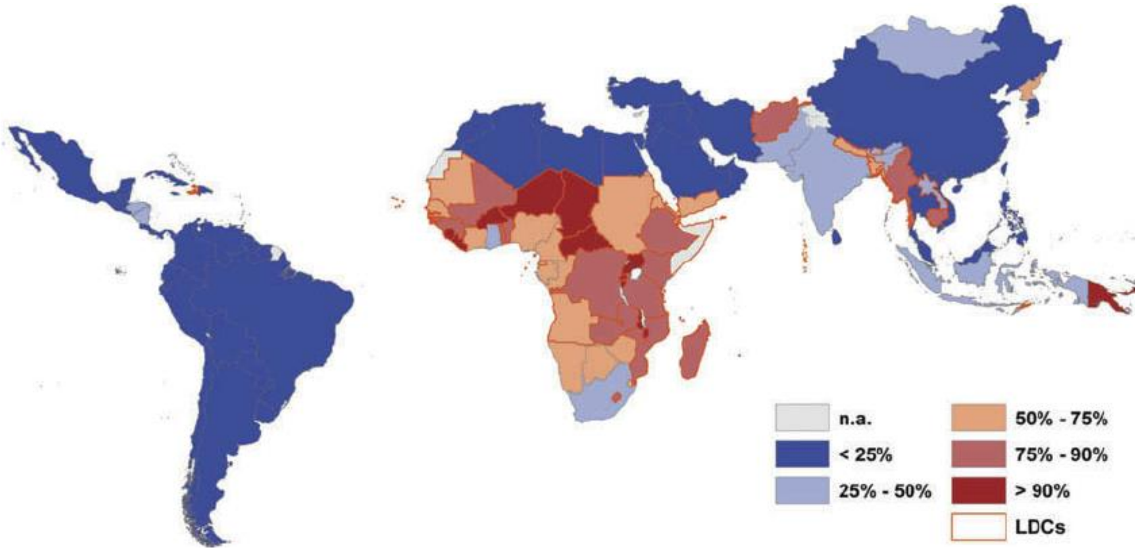

Figure 15 Share of people without electricity access for developing countries

Source: Garg & Joshi 2014

Photovoltaic panels are nowadays often used in street lighting systems to generate electricity. Thanks to them, businesses and industries to reduce their electricity bills and achieve their environmental goals. They are placed in rural regions with little or no access to the electricity grid. Because they can run independently of the grid, which makes them suitable for remote agricultural applications, they are frequently used for agricultural irrigation, livestock watering, and water supply in rural areas. They also supply dependable power for telecommunications equipment, monitoring stations, off-grid cabins, and remote communities. A PV solar energy-driven reverse osmosis (RO) system presents as a promising solution for remote and isolated regions grappling with electricity shortages and limited access to potable water. This approach is poised to emerge as the most energy-efficient technology among various desalination methods (Garg & Joshi 2014).

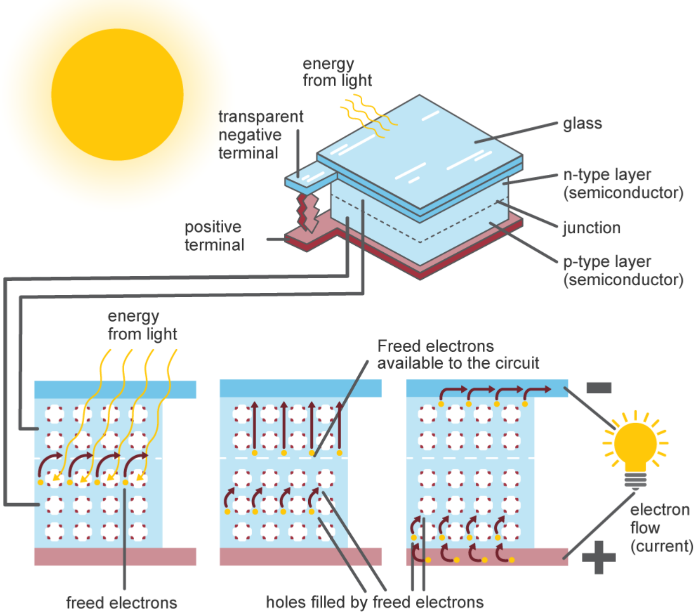

Figure 16 Inside a photovoltaic cell

Source: U.S. Energy Information Administration

The scholarly discourse surrounding solar energy entails an interdisciplinary exploration of its technological, economic, environmental, and practical dimensions, highlighting its pivotal role as a sustainable energy solution amidst the global transition towards a low-carbon future.

4.4. Application of renewable energy pumps in selected countries

These nations should be taken into consideration when talking about renewable energy-powered water pumping solutions in arid or semi-arid regions because of their extensive expertise and current activities in this area.

4.4.1. Africa

Africa is the region with the least amount of water security, experiencing severe shortages of water. The “Mother Continent” faces both types of water scarcity, physical (the main cause being overexploitation) and economic (lack of funding, innovation, and strong institutions, resulting in poor water management and/or inadequate infrastructure, etc.). The World Health Organization reports that 1 in 3 Africans lack access to clean water and that the situation is getting worse because of population expansion, urbanization, and climate change. According to experts, 460 million people in Africa will live in water-stressed areas by 2025. It is compulsory to solve this escalating catastrophe by finding practical solutions for Africa's water deficit.

The region has had some of its most severe droughts in terms of physical water insecurity. Mainly because of human activities, Africans are being forced to travel unbelievable distances in search of clean water as lakes and rivers that formerly supplied an abundance of water are drying up. Only one-third of South Africa's rivers are in decent condition, and more than half of them are overfished. Overexploitation is causing Lake Chad, which was once Africa's biggest freshwater supply, to diminish.

A large amount of physical water scarcity exists in dry regions, mostly in North Africa. Yet, economic water shortage is most common in Sub-Saharan Africa where the population without access to water is increasing which only occurs here. In Sub-Saharan Africa, 387 million people lacked access to basic drinking water services in 2020, in comparison to up to 350 million in 2000, according to the WHO/UNICEF Progress Report (World Bank Group 2024).

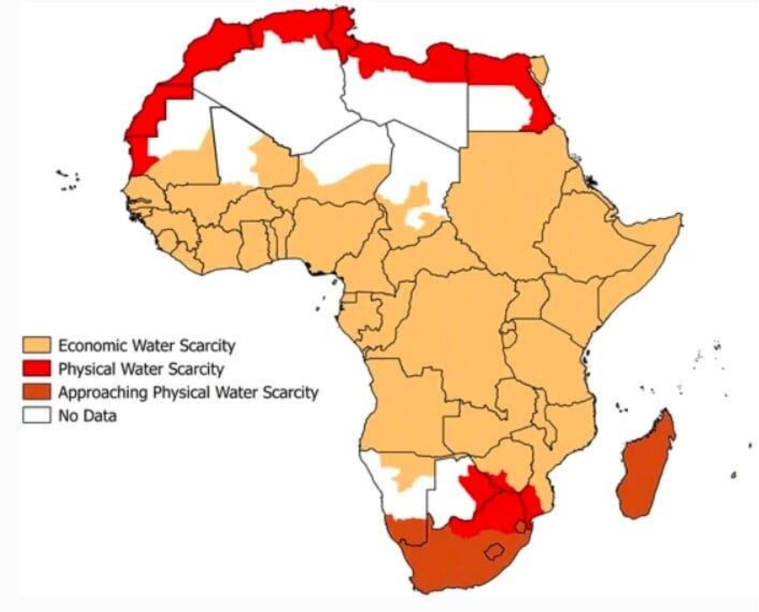

Figure 17 Water Scarcity in Africa

Source: Genesis Water Tech 2023

Cape Verde, Egypt, Morocco and South Africa hold significant importance when discussing solar and wind-driven water pumps in Africa:

- all of their governments are committed to achieving sustainable goals (reducing GHG emissions and promoting renewable energy)

- they have a variety of topographical characteristics making it possible to use wind and sun energy for water pumping and are in the ideal position to take advantage of the wind and sunlight that blow through their region

- all of them suffer from water scarcity and also have significant potential for renewable energy, especially in the areas of solar and wind power

- the installation of solar and wind-powered water pumps in these nations is actively being supported by international organizations, governments, and non-governmental organizations (NGOs) as part of larger development initiatives in order to eventually increase agricultural productivity, economic growth in rural areas, and overall access to water

4.4.1.1. Cape Verde

In addition to changing economies, populations, and political scenery, African nations deal with the consequences of global warming, all of which might impede the ongoing development of water management systems. Their water shortage complicates water quality issues and water management entities also must face increasing population growth which creates higher demand, especially on small islands the conditions for safe supply are jeopardized by the salinization of the groundwater resources.

On the largest and most populous island in a group of arid Atlantic Islands, a developing state Cape Verde a quarter of the population “uses wells, springs, and other potentially non-potable sources” (Gonçalves 2019). Cape Verde is experiencing more and more dehydration because of its greater vulnerability to climate change. This could result in higher water needs, coupled with its existing population growth tendencies. Socioeconomic progress faces obstacles due to the cost, accessibility, and sustainability of energy and water. Africa is generally in the same predicament.

Access to water in developing economies tends to rely on neglected reservoirs such as rivers, ponds, and springs. Infrastructures supporting distribution and exploitation usually are lacking or cause problems with governance. In the absence of an efficient public network, water vendors may provide it forcing the population to walk long distances, which is a task commonly given to youths and women.

4.4.1.2. Egypt

Egypt suffers shortage of water resources. In the Red Sea Governorate, 0,2% of all Egypt population lives in a territory of a fifth of the whole Egypt area which makes it challenging to make investments. Additionally, there are mountains along the Red Sea shore and no railways, so the piping works and fuel transportation are expensive. Luckily, there are places where strong winds are consistent throughout the year, enabling wind power generation and the resulting production of water. The mechanical vapor compression desalination system (MVC) is one of the seawater desalination methods designed for remote locations. The primary disadvantage of wind-powered devices is their fluctuating wind speed (Karameldin 2003).

4.4.1.3. Morocco

Morocco features both dry and semi-arid areas, particularly in the south and interior. In these regions, water supply, agriculture, and the fight against desertification are all enhanced by wind-driven water pumps.

As a result of climate change, Morocco is anticipated to have a serious water deficit driven by either an increase in water demand or a decrease in P and lack of water with changes in agricultural yields might ultimately cause the loss of numerous employment possibilities, mainly in the country's rural areas. Eventually, they may result in fewer irrigated fields and lower agricultural output in the country. With all other things being equal, it is predicted that these adjustments will result in a decrease in agricultural and food product output and an increase in crop prices of up to 14.3 percent but several of these negative effects can be avoided by investing in water-saving techniques and switching to more profitable and less water-intensive crops (Taheripour et al. 2020).

Well-suited to the climate of Morocco would be olives, almonds, dates, and figs production as all of the crops mentioned are drought tolerant and require minimal water usage.

The new water strategy went into effect in 2009 and is planned to support the development of the water needs for development until 2030 by implementing an integrated policy that combines resource mobilization in water resources via water conservation, while protecting the environment and future generations' rights. The three main focuses of the plan are supply development and management, water demand management and valuation, and preservation and protection of the environment and water sources (Mohamed 2013).

In Morocco, Law 36-15, also known as the Water Law, was enacted in 2016. It highlights the necessity of decentralized, integrated, and participatory water management and acknowledges the significance of creating planning tools to deal with water scarcity (Bekhechi 2017).

4.4.1.4. South Africa

There are semi-arid areas in South Africa, especially in the Northern Cape and several of the provinces in the Western Cape. In these regions, wind-powered water pumps are used for rural water delivery, animal irrigation, and crop irrigation.

South Africa´s legislative capital Cape Town is characterized by excessive disparity. In early 2018 in Cape Town the worst drought ever was recorded, which threatened to turn off taps for 4 million people in their homes. Racial inequality's legacy, which affects water justice, is still a problem in South Africa. The City of Cape Town increased the scope of its water demand management program, which includes public awareness-raising campaigns, pressure reduction, and leak repairs, during the current drought. Cape Town is currently looking into other water sources and creating a new water strategy (Enquvist Ziervogel 2019). The WPC in South Africa is 1,000 m^3/person/year. When comparing South Africa to its neighbors, their water availability per person is higher than South Africa's because the neighbors' water comes from either lower population centers or higher rainfall sites (Bwapwa 2018).

According to estimates, the risk that a drought in South Africa would occur has quadrupled due to climate change (Otto et al., 2018). The main national regulatory frameworks for water usage in South Africa are The National Water Act (how water may be obtained and utilized) and the Water Services Act (which institutions should be in charge of providing residents with water-related services). Through its Water Resilience Programme, the city began looking at the costs and delivery times of several solutions in 2017 and started developing a new water strategy. Even if rainfall is not always consistent, surface water is still the most economical and abundant supply and will remain so (Enqvist Ziervogel 2019). To push for water justice, governance must take the city's growth and the development of water supplies into consideration and must be universal.

The mentioned countries exemplify the potential of solar and wind-driven water pumps to mitigate water challenges, foster sustainable development, and propel the transition towards renewable energy in the African context.

4.4.2. Asia

Central Asia is one of the dry regions most susceptible to water constraints, with its food security mostly reliant on irrigated agriculture. Inevitably, despite the impending dangers from a warming perspective that is higher than average and the anticipated melting of glaciers, which will have an impact on the supply of irrigation water, sensitivity to climate change is rarely taken into consideration.

Humans rely on fresh water for three main purposes:

- domestic activities,
- agricultural practices,
- industrial activities for non-agricultural commercial purposes.

Agricultural needs notably increase minimum water requirement estimates, with approximately 70% of global freshwater withdrawals allocated for agriculture. Countries respond to dwindling water availability by enhancing water resource efficiency, reducing wastage, and prioritizing water allocation for more economically productive uses.

To address escalating water scarcity, one strategy involves trade, where countries increasingly rely on food imports, often referred to as "virtual water," to meet their essential food supply demands.

With the ongoing expansion of socioeconomic development and interregional trade and commerce, the virtual water flows associated with the circulation of commodities are growing at a rapid pace. The regional water resources system has a major impact by both physical and virtual water flow related to socioeconomic activities. Comprehending virtual water allows the estimation of the indirect water usage related to the manufacturing and utilization of products and services. Tt enables more effective management of water resources and trade decisions, which makes it important in regions where a lack of water is an issue.

For this analysis, three countries were chosen to be described – China, India and Pakistan. They all are relevant because of common characteristics:

- possess large populations and strong agricultural industries that require access to continuous water supplies. Irrigation systems that are affordable and sustainable could be facilitated through renewable energy-powered water pumping solutions,
- encounter concerns with water scarcity as a result of urbanization, climate change, and rapid population increase. Water pumping systems driven by renewable energy are capable of collecting water from wells, streams, etc. for a variety of applications (industrial processes, drinking water supply, irrigation, etc.) which helps lessen the availability of water
- have accelerated their energy consumption to fuel their industrialization and economic growth. In keeping with their pledges to fight climate change, integrating renewable energy sources like solar and wind for water pumping can help diversify the way they generate electricity, decrease their dependence on fossil fuels, and cut greenhouse gas emissions.

4.4.2.1. China

Several Chinese areas are dry or semi-arid, including sections of the provinces of Gansu, Xinjiang, and Inner Mongolia where wind-powered water pumps are used for rural water delivery initiatives, agriculture, and desertification management. China has been making investments in renewable energy technology but despite its large agricultural area still confronts difficulties with water management, such as groundwater depletion and water shortages. A study conducted by Dr. Jingxue Wei, Dr. Yalin Lei, and other Chinese scientists revealed that in Yellow rivers basin, once water quality is taken into consideration, the number of cities undergoing severe water stress rises from 13 to 53 and ultimately, they found out that "ignoring water quality will underestimate the risk of direct economic loss due to local water scarcity" (Wei Lei et al. 2023). The industries that were most at risk when looking simply at water quantity were agriculture, metal smelting, rolled goods, chemical products, and construction. Not only was water shortage a major contributing factor to the possible economic losses in the metal smelting, forestry, and fisheries goods and services sectors, but water pollution also played a major role.

4.4.2.2. India

Arid or semi-arid climates may be found in several parts of India, including Rajasthan and areas of Gujarat. In these regions, wind-powered water pumps are being used for community water projects, agriculture, and drinking water distribution. With advanced irrigation systems to sustain its agricultural industry, India is among the world's biggest manufacturers of agricultural products. The nation has been progressively implementing renewable energy-driven water pump technologies, such as solar-powered pumps, to decrease its dependency on fossil fuels and boost irrigation efficiency.

The country's expanding population is driving up water consumption in India. Fossil fuels provide around 16.5% of the power utilized nationwide to pump this water, increasing pump Life Cycle Cost (LCC) and Green House Gas (GHG) emissions (Angadi 2021).

In India, the development of renewable energy sources has a long history dating back around 110 years, which is equal to the history of electricity development. The first run-off-river hydroelectric station, with a capacity of 130 kW, was established in Sidrapong, Darjeeling, in 1897 (Jain 2014).

Figure 18 Wind pump construction in India

Source: Pavol Floriš 2016

4.4.2.3. Pakistan

Pakistan has less rainfall and year-round semi-arid weather which makes the conditions more difficult. Its economy is based on agriculture, and agricultural output is heavily dependent on irrigation. The nation has been using solar-powered water pumps to increase agricultural output, lower energy costs, and improve water availability, especially in isolated and off-grid areas. „The unequal distribution, coupled with population pressure, rapid urbanisation, and increasing industrialisation, poses a serious challenge to water management in Pakistan in the 21st century" (Shezad Siegmann 2006).

Pakistani agricultural output is mostly dependent on irrigation water, necessitating the development of a strategy plan for sustainable water management. Nonetheless, some of the most important problems endangering the agriculture industry are those related to surface water recharge, metal toxicity, water logging, salinity, and sodicity. Upscaling of contemporary technology, enhanced agricultural education, and training, higher-quality inputs for better irrigation, reclamation of saline/water-logged soils, increased emphasis on credit and support prices for water inputs, and enhanced water conservation methods are proposed as prospects. Innovations in irrigation water management, the release of heat- and drought-tolerant cultivars, the development of reclamation and drainage techniques, and the upgrade of extension services are among the recommendations (Wajiha 2021).

Several actions have been suggested by the FAO to assist members in establishing a supportive domestic environment for the growth of sustainable aquaculture. Integrated aqua-agriculture systems have the potential to generate significant economic benefits and facilitate the year-round production of premium fish, vegetables, and fruits.

In alignment with their commitments to mitigate climate change, the integration of renewable energy sources such as solar and wind for water pumping can facilitate diversification of electricity generation methods in the aforementioned countries. This approach aims to reduce reliance on fossil fuels and consequent GHG emissions.

4.4.3. Latin America

Although water resources in Latin America and the Caribbean (LAC) account for around 35% of the world's renewable water resources, the area is becoming more concerned about water shortages due to issues with resource management and unequal access to water. Reusing greywater (wastewater produced by households) might be a useful and dispersed way to recycle water, which would lessen the effects of scarcity in remote or challenging-to-reach places. As Rodríguez (2022) suggests, financial factors must be carefully considered when managing and regulating greywater reuse in a decentralized way, since treatment systems may be too expensive for those who can reuse.

In Latin America around ¾ of renewable water resources are needed for agriculture, making it one of the water-hungry industries in the world. Less than 80% of people in seven nations (Haiti, Nicaragua, Bolivia, Guatemala, Honduras, El Salvador, Paraguay) have access to clean drinking water, making it scarce in rural regions. According to the World Bank (Water Matters 2023) over the last two decades, Latin America went through 74 droughts, resulting in damages of over US$ 13 billion. The output of crops and cattle as well as farmers' livelihoods are impacted by this phenomenon, especially those living in precarious situations.

Water is comparatively abundant in LAC. There are renewable water resources per capita in LAC covering an area of more than 14.8 million km^3 annually on average greater than 20,000 m^3 but in large regions (Argentina, Bolivia, Brazil, Chile, Mexico, Peru), its geographical and temporal dispersion results in water shortage. LAC also shows several issues with water management and governance (Rodríguez et al. 2022).

Below are Latin American nations that are important areas where energy-driven water pump systems may significantly enhance rural development, agricultural output, and water management. In particular, my research will concentrate on Brazil, Chile, and Mexico due to their significance in the context of:

- their rural communities being heavily dependent on agriculture and having issues with accessing dependable energy sources. Energy-driven water pump systems can support rural livelihoods and promote socioeconomic development in these areas by reliably providing water for household usage, livestock watering, and irrigation,
- water stress and scarcity they face which are prevalent in many regions of Mexico, Chile, and Brazil as a result of causes such as irregular rainfall patterns, droughts, and mismanagement of water resources,
- having a variety of topographical characteristics, but energy-driven water pump systems can be modified to meet specific needs. This would allow for the distribution, irrigation, and extraction of water, and eventually maximize the use of water resources and agricultural output.

By providing off-grid options for water pumping, energy-driven water pump systems lower the reliance on centralized grid infrastructure and increase access to contemporary energy services in isolated and underserved areas.

Figure 19 Water Stress Exposure in Latin America in the 2020

Source: Water in Latin America 2022

4.4.3.1. Brazil

With an estimated twenty-seven million people living there, Brazil's semi-arid regions (BSAR) are the most densely inhabited semi-arid areas situated in the nation's northeast, which is home to most of the nation's socially and climatically more susceptible cities. With an average annual rainfall of 750 mm, BSAR are thought to be the planet's rainiest semi-arid area. Out of almost 50 drought events thus far, a third of the has persisted for at least two years in a row. Despite this, they have a highly variable rainfall regime with sporadic and protracted droughts. Eventually, it is anticipated that BSAR will experience a sharp decline in P in the upcoming years, which will have significant social repercussions (Ledru et al., 2020).

In BSAR, they inserted cisterns and public irrigation schemes between the years 1995 and 2017. A study (Silva et al. 2021) tried to evaluate the relevance of a rise in access to water and its impacts on family farming agricultural development and discovered that while agricultural irrigation systems achieved better results, villages that had more cisterns did not achieve satisfactory agricultural development, and almost all of the municipalities observed a decrease in agricultural productivity. “Regarding physical-natural conditions, subsurface runoff has decreased and an increase in surface runoff was identified, which can be collected through the installation of new cisterns” (Silva et al. 2021). To overcome a situation of high social vulnerability combined with environmental degradation, public policies are essential (Vieira et al., 2020). Up to the 1990s, BSAR were helped by ineffective, if not nonexistent, governmental policies that promoted the installation of tiny reservoirs that were extremely susceptible to droughts and well drilling in areas with crystalline rock and rural farmers knew very little about sterns and other drought-resilient technology. The Brazilian Semi-Arid Articulation network's One Million Cisterns Program (P1MC) has been a driving force behind the expansion of water access initiatives in the region since 2001. It was added to the public policy agenda in 2003, and the federal government began funding and supporting it through the Brazilian Ministries of Fight against Hunger and Social Development. The primary goal of the initiative is to guarantee that families in the remote parts of BSAR towns have access to potable water by building cisterns. Schemes for public irrigation supporting small farmers and specializing in BSAR are also funded by the government. Since management organizations have not created a system to evaluate the economic sustainability and overall performance of public irrigation schemes, their technical performance is seriously under scrutiny (Mateos et al., 2018).

4.4.3.2. Chile

Chile has a vast coastline with a wide range of climates, including semi-arid and dry areas where there is a risk of water scarcity. To meet its energy demands responsibly and improve the efficiency of its water pumping system, the nation has been investing in renewable energy projects, among them those using solar and wind power. Water shortage in Chile is a complicated problem that is made worse by things like population increase and intense mining. Surprisingly, as Bitrán (2014) found out, the overuse of groundwater resources has continued despite complete private ownership and unrestricted trading of water rights. Large amounts of water are required in Chile's water-scarce areas for mining, coupled with small towns and agriculture. The mining industry's need for more water has sparked a discussion about legislation that would expand the usage of saltwater. However, the regulatory structure is insufficient (Alvez at al. 2020).

Eleven industrial-scale desalination facilities operate in Chile, generating 5,868 liters per second of desalinated water. Desalination can enhance water security and provide alternative source of freshwater, but also requires high capital, operating costs, and large amounts of energy to operate. Other problems that the country faces are high energy usage of water delivery systems, the disposal of desalination concentrate, and damaging algal bloom occurrences (Herrera-León, 2019).

Only a Chilean bill to regulate the reuse of greywater is approved, “approved Law N° 21,064 allows for a greater control and administrative intervention of the DGA focused on groundwater availability” (Gobierno de Chile, 2018), other countries that have bills to regulate the reuse of greywater in Latin American region are Brazil and Peru.

4.4.3.3. Mexico

Mexico faces difficulties with water management due to its varied climate, is also vulnerable to recurrent flooding. In Mexico, renewable energy sources like solar and wind power are becoming more popular. This presents chances for energy-driven water pump systems in agricultural and rural areas.

Mexico's water resources are ranging from extreme shortage in the north to abundance in the south. The country's center to northern areas is semiarid and arid. Inadequate treatment facilities and areas of obvious contamination have long been recognized as environmental breakdowns that harm ecosystems and human health. The government is addressing the effects of impairment through improved initiatives and new public policies (Singh 2020 & Otazo-Sanchéz 2019). In Mexico´s most populous city, Mexico City the water availability is 130 liters per person per day, which is less than needed. Additionally, inadequate infrastructure and mishandling of water resources alone account for half of Mexico City's water supply loss but various areas of potential are shown to lower energy use and clean up Mexico City's unsustainable water usage pattern (Salazar et al. 2012). However, the situation is expected to worsen in the future, necessitating the development of additional water resources and improved management practices (Barker 2000).

A community-based water system project in Mexico known as SAPTEMAC (in Spanish acronym for Sistema de Agua Potable y Tratamiento de Aguas Residuales para la Cuenca del río Mazatán en Chiapas), Potable Water System and Wastewater Treatment for the Mazatán River Basin in Chiapas) has a goal to provide communities in the state of Chiapas' Mazatán River Basin with drinkable water and wastewater treatment services and assures underprivileged people access to water and sanitation facilities in Mexico. In the aim of SAPTEMAC, there is planning, implementing, and managing water supply and sanitation systems with community involvement. Out of the six water wells that this civic organization maintains, five supply water to about 4,000 outlets in the municipal head.

SACMEX is a government organization in Mexico City (Sistema de Aguas de la Ciudad de México - The Water System of Mexico City) that oversees drainage systems, wastewater treatment, water resources, and water delivery.

Energy-driven water pump systems have the potential to play a transformative role in enhancing rural development, agricultural productivity, and water management in Mexico, Chile, and Brazil, tackling urgent issues including energy access, water scarcity, and environmental sustainability while promoting equitable and sustainable growth.

5. Conclusions

To summarize the key findings of the Bachelor thesis, there is SWOT analysis demonstrating an understanding of the strengths, weaknesses, opportunities, and threats of the discussed topic.

The strengths of these systems are evident in their ability to harness renewable resources like solar and wind energy, which are abundant in arid regions. This not only helps in mitigating water scarcity but also in reducing dependency on non-renewable energy sources, thus contributing to environmental sustainability.

However, the weaknesses of such systems include the high initial costs of installation and the technological complexities involved in maintaining and optimizing these systems in diverse geographical and climatic conditions. Despite these challenges, the opportunities presented by renewable energy-driven water pumps are significant. They offer a sustainable solution to water scarcity challenges, enhance local capabilities through the adoption of green technologies, and potentially stimulate economic growth by increasing agricultural and domestic water supply in underserved regions.

On the threat front, variable climatic conditions pose a significant risk to the consistent performance of solar and wind-driven systems. Additionally, the lack of local expertise and the need for regular maintenance can hinder the scalability and sustainability of these technologies in target regions.

Overall, the conclusions drawn from this thesis emphasize the imperative for strategic planning and policy advocacy to optimize the efficacy of renewable energy-driven water pumping systems. Through mitigating the identified weaknesses and threats while capitalizing on strengths and opportunities, these systems stand poised to substantially contribute to the advancement of sustainable development and enhancement of water security within arid and semi-arid regions on a global scale.

Suggestions for the design and installation of solar and wind-powered water pump systems in arid and semi-arid areas in the future would include becoming green and sustainable which is a priority for The United Nations Development Programme. To prevent the disastrous effects of climate change, greenhouse gas emissions must be cut in half by 2030 and reach net zero by 2050 to keep global warming to 1.5°C. By implementing using of wind- and solar-powered water pumps this could be a reality in the future. Island locations, coastal zones, and mountainous regions are particularly favorable to wind power, which makes it a desirable energy source for desalination operations in these environments. As long as the wind equipment is placed properly, wind energy can be used continuously, unlike solar energy, which depends on the presence of sunshine. This feature makes wind power the better choice when it comes to maintaining continuous operations with less dependence on long-term energy storage options than solar energy, especially in areas with abundant wind resources (Malek et al. 2016).

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