Dimensioning an Off-Grid Solar Pumping Installation for an Aquifer Storage and Recovery System in Texel – Netherlands

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Abstract **- The agricultural sector in the Netherlands, namely on the island of Texel, has been affected by water scarcity issues in the last five years, causing a significant decrease in production. The joint effort of a group of farmers from the island, local and national governmental members, and the consulting firm Acacia Water intends to tackle these issues by developing an Aquifer Storage and Recovery (ASR) system under the Zoete Toekomst Texel (Sweet Future Texel) project. This project aims to create a sustainable and energy-neutral agricultural system in Texel, so an off-grid photovoltaic (PV) system will be installed to feed the ASR system's water pumps.**

In this study, the water pumping requirements for this ASR system are dimensioned and the feasibility of installing a PV system are estimated. The study includes assessing the energy demand of the ASR system, evaluating the solar energy availability in Texel, and defining the optimal sizing and configuration of the PV system's components. The ASR system pumps consume a maximum of 6.45 kW. A PV system providing this amount of power was designed. During summer, a relatively small number of solar panels is required to provide the necessary power for the water pumps, and the feasibility of the PV system is confirmed. However, the number of solar panels required during winter is almost five times higher, justified by the very low incident solar energy and the much higher power that the pump operation requires. In this period, the agricultural plots' owners must evaluate the feasibility of the proposed solution.

Despite providing a good indication of the suitability of solar pumping for an agricultural water management system such as an ASR, there are still some crucial points that this research could not tackle. Further investigation into these points will contribute to a better overview of the feasibility of the intended system.

Key-words
Off-grid PV System, ASR System, Solar Pumping, Water management

I. INTRODUCTION

Humanity has been consuming fossil fuels at an ever-increasing rate to generate energy. Acknowledging the finite nature of these materials and the harmful effects of their consumption, with the most relevant being climate change and air pollution, a shift towards using sustainable energy solutions has occurred. One of the key parts of this transition is Solar Photovoltaic (PV) energy.

Solar PV energy has many benefits. It is clean since it does not release harmful substances into the atmosphere and is renewable because sunlight is abundant. Solar PV systems can have low operating costs, low maintenance, and a relatively long expected lifespan. For these reasons, it is an energy source that can be used in various sectors, from domestic to large-scale electricity generation.

Agriculture is one of the sectors that have benefitted the most from the technological developments of solar PV systems. Many processes utilized in modern agriculture rely on large volumes of electricity. Water pumping systems are one of the major sources of electricity consumption in agriculture, and solar PV systems are seen as a cost-effective alternative to traditional diesel generator-fed or grid-connected pumps.

Regarding agricultural water pumping, the main advantage of utilizing PV systems is that they can be installed in remote locations where connecting to the electric grid is difficult.

A growing interest in the concept of “solar pumping” has been identified over the last decades, and research has shown some promising examples of this type of technology. However, further investigation is necessary to understand the influence of different factors on the feasibility of solar pumping systems.

Another factor that leads farmers towards innovative pumping solutions is the growing importance of responsible water management due to the increased drought periods and the decreased availability of freshwater sources. This concerns designing optimal pumping and irrigation systems and exploring new ways of storing and reutilizing water.

The combination of the scientific interest in investigating the possibilities of solar pumping with the environmental challenge of improving water management in agriculture led to the development of this Thesis Dissertation project. It took the form of a six-month internship program in which the author cooperated with the Dutch company Acacia Water and in which the case study was the Zoete Toekomst Texel project.

The Zoete Toekomst Texel is a project in which various governmental and environmental organizations cooperate, and Acacia Water is one of the major shareholders in tackling the water scarcity and drought periods in Texel. This project's main focus is designing an Aquifer Storage and Recovery (ASR) system. Such a system consists of a drainage grid, a water filtering facility, a pumping system, and an aquifer capable of reserving high volumes of water. The premise is that this ASR system can direct surplus rainwater from the agricultural plots into the aquifer and, in the opposite direction, provide crops with sufficient fresh water even during drought periods.

Solar PV energy is used in the Zoete Toekomst Texel project to provide a sustainable and reliable energy source to power the entire ASR system. It is intended that using PV energy can reduce energy costs and carbon emissions while improving water use efficiency and sustainability.

With its benefits and challenges, this project expects to achieve positive outcomes by using PV energy to feed an ASR system. It aims to reduce energy costs and carbon emissions, improve water use efficiency, and reduce the dependence on external water sources in Texel, contributing to a higher resilience of its agricultural system to drought. Most importantly, it aims to demonstrate the feasibility and the benefits of adopting PV technology in ASR systems for agriculture, ultimately encouraging the adoption of this technology more often in the future.

II. CASE STUDY

The Zoete Toekomst Texel project started as a partnership between Dutch environmental organizations, Acacia Water, local governmental entities, and a group of farmers from Texel who agreed on having their agricultural fields serve as a “pilot” for the first steps of the project to take place in.

The project was designed looking at a medium to long-term completion, and its experimental nature was stated from the beginning. In practical terms, the result would be that every farmer had its own ASR system and, ideally, that the collected rainwater would provide their crops with sufficient water to maintain competitive production volumes and quality.

This chapter is divided into two sections. The first one intends to evaluate the technical aspects of the ASR system, providing a detailed description of its components, their performance, and their impact on the overall operation of the system, as well as possible improvements. The second section considers this insight for designing the related PV system and integrating it with the pumping needs of the ASR system.

A. ASR System Description

The ASR system that this study refers to is located in the Hoofdweg agricultural plot in the northeastern part of the island and represents the first experimental design implemented by Acacia Water for the Zoete Toekomst Texel project. The picture below presents a top view of the plots.

Figure 1 - Top-view of the agricultural plots

The agricultural area intended to irrigate consists of three plots with different necessities concerning irrigation volumes and the duration of the crop growth seasons. A parcel with an area of 90 hectares where potatoes are predominantly grown, referred to as “Broekman plot 1” in Figure 1, a second parcel with the same area where predominantly livestock-feeding grass is grown, referred to as “Broekman plot 2”, and a third parcel with an area of 139 hectares where sugar-beets are predominantly grown, referred to as “Slot plot”. The names in the figure identify the farmer that owns each parcel. With these three types of plants being the ones that make, by far, the highest production volumes, the water volumes that the ASR system needs to collect and recover are based on their growth necessities. The table below represents the dimensions of each plot:

Table 1 - Dimensions of the agricultural plots

Plot dimensions	*Broekman 1*	*Broekman 2*	*Slot*
Length 1 [m]	625	625	550
Length 2 [m]			390
Width [m]	150	150	300
Total Area [m²]	93750	93750	141000
Effective Area [m²]	90000	90000	139000

An overview of this particular ASR system is illustrated in the diagram below.

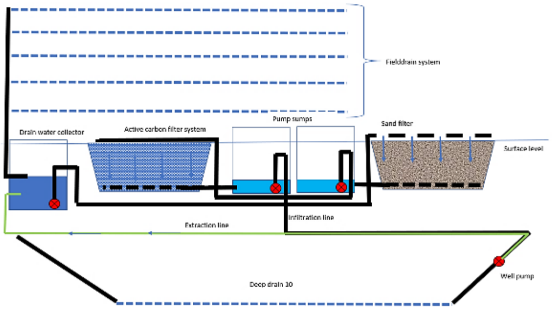

Figure 2 - Schematic diagram of the ASR

As seen in Figure 2, there are, in such a system, 3 different pumping stages. The first pumping stage concerns drainage, capturing groundwater in the fields, and moving this captured water volume into the next stage. This next stage is the filtering system, composed of a sand filter and an activated carbon filter. A pump is needed for the water to flow from the sand filter into the activated carbon filter and, further ahead, from the activated carbon filter into the well. Finally, the third stage concerns the extraction of water from the well. These stages are now described in more detail.

1) Drainage

Before reaching the pumps, rainwater hits the ground and infiltrates the soil, forming what is known as a groundwater layer. Below this groundwater layer, in each parcel, a set of drainage pipes, placed horizontally at 80 cm depth and with a distance of 50 cm between them, ensure the maximum possible drainage flow into two "collector pipes" placed at the extremities of each parcel, which finally lead the water into the respective pumping compartment. The design and dimensions of the drainage system are illustrated in the figure below, as well as the drainage pumps and pumping station location.

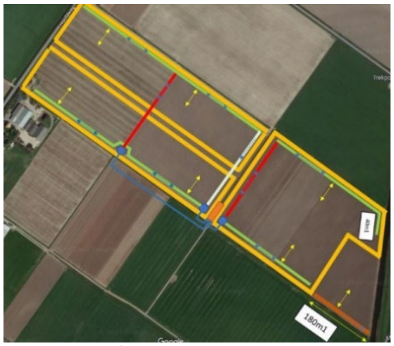

Figure 3 - Top-view of the drainage systems, with the drainage pumps in blue, the drainage pipes direction in yellow and the collector drains in green

2) Filtering

A double filtering system is placed between the pumps and the wells, consisting of two rectangular-shaped compartments immediately. The first filter comprises three types of sand of different granularities to filter particles of differing diameters. The first layer is composed of a thicker grain type, filtering larger particles, while the third layer is composed of thin sand for filtering smaller particles. Another submersible water pump is used to pump water from the sand filter into the second compartment, which constitutes the activated carbon filter, whose objective is to decompose the biochemical substances that originated in the field water due to pesticides and fertilizers. A final water pump is used to pump filtered water into both wells, going immediately through a cabin where its quality can be assessed and where different piping paths lead it to its intended well. Both filter compartments are equal in volume and construction. The images below illustrate the design and dimensions of both filters.

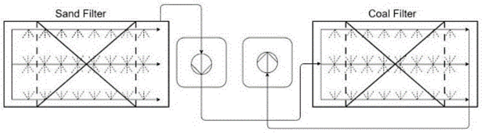

Figure 4 - Illustrative diagram of the filtering system

3) Injection and Recovery Wells

During winter, water is injected into one of the extremities of each well by the action of the second filtering pump, while during summer, when recovery is required, an additional submersible pump is placed at that same well extremity for both wells to pump the water directly back into the groundwater layer, increasing the groundwater level and allowing for the crops' roots to receive the required water volumes through natural sub-irrigation. The other extremity of both wells remains permanently closed except for required maintenance and cleaning periods. The location of the recovery pumps is identified in white circles in Figure 5.

Figure 5 - Top-view of the agricultural plots identifying the location and length of the injection wells

B. Performance Assessment

Analyzing each part of the system as isolated, with an input-specific performance, namely losses, efficiency, and output, is considered advantageous. Therefore, the drainage, filtering, and pumping systems are studied separately, and their interactions are clarified.

1) Drainage System

The drainage system's performance depends on several factors. First, it depends on the input, which can be seen as the total volume of water entering the drains. This volume is defined by the precipitation volume, the evaporation losses, and the influence of the soil dynamics, namely the depth of the groundwater level and the soil conductivity.

It also depends on the design of the drains, as described in the previous chapter, concerning their length, the spacing between drains, the depth at which they are installed, and the slot diameter and distance between slots. All these factors influence the drainage rate and, therefore, the drainage efficiency.

Due to the saline environment of the island, another important factor to consider is the useful percentage of drainage water, that is, the percentage with an electric conductivity value lower than the allowed limits and that will, therefore, be stored in the aquifer. Using electric conductivity sensors, an initial selection is made between drainage water going to the aquifer and drainage water going to a nearby ditch. It is important to make sure that, once the aquifer water is recovered, it meets the quality requirements of the crops and, importantly, that the aquifer does not get filled with saline water, which would damage its properties.

Broadly, it may be considered that the drainage output consists of the difference between precipitation and evaporation, water retention on the soil due to its properties, and volumetric capacity of the drains, and there are both steady state and non-steady state equations to calculate drainage flow rates. Due to the high precipitation volumes occurring in this area, steady state equations do not provide valid results in calculating these flow rates, and due to insufficient hydrogeology knowledge, the fact that it is ultimately a secondary subject for the intended study, and the inherent complexity of calculating drainage flow rate using a dynamic equation, it was chosen to utilize existing data from a different location with similar hydrogeological properties as a base for the results to be achieved.

This data presents the daily measured drainage flow rate, precipitation, and evaporation in the Breezand region over two periods: from the first of April 2014 to the first of April 2015 and from the first of April 2015 to April 2016. The drainage system design is similar to the one in Texel, with the same drain type, depth, and distance in between.

The estimate of the drainage discharge is Texel was done using a proportion between the field areas and the precipitation and evaporation values on both sites.

Table 2 - Estimated water balance of the 90 hectares plots

90 ha plot water balance	*2015*	*2016*	*Total*
Number of days	356	296	652
Drainwater			
To ditch [m^3]	113888	153288	267175
To ASR [m^3]	293616	119534	413149
Total [m^3]	407503	272821	680324
To ASR [m^3/h]	34.4	16.8	26.4
To ASR during winter [m^3/h]	28	14	42

Table 3 - Estimated water balance of the 139 hectares plot

139 ha plot water balance	*2015*	*2016*	*Total*
Number of days	356	296	652
Drainwater			
To ditch [m^3]	175893	236744	412637
To ASR [m^3]	453473	184613	638086
Total [m^3]	629366	421357	1050723
To ASR [m^3/h]	53.1	25.9	40.8
To ASR during winter [m^3/h]	43	21	64

The values presented in both tables above represent, from the precipitation values from the 2015 and 2016 periods, the percentage that is useful and possible to drain into the aquifer. Due to the saline influence on groundwater, a significant part of the drainage volume cannot be recovered and must be discharged into the nearby ditch. The average drainage efficiency over these two periods is 61%. Finally, with the estimated values presented in the tables, most importantly with the average winter infiltration flow rate, the drainage pumps of each plot can be dimensioned. Taking the conservative choice of selecting pumps capable of providing the average winter infiltration flow rate, the 90 hectares plot must use pumps with a maximum flow rate capacity of 28 m^3/h, while for the 139 hectares plot, the pumps must be capable of a maximum flow rate of 43 m^3/h. When these flow rates are exceeded, the buffering compartments should allow most of the water volume to accumulate. However, these compartments were not dimensioned, taking this into account.

The daily periods during which the pumps should operate are more restricted if the initial proposed system design is considered. If, for example, a drainage pump provides a flow of 28 m^3/h during 8 hours because solar power is only available during this period, then accumulation should be possible for 16 hours, resulting in a total volume of almost 450 m^3 of water. This would only be possible with much larger buffering compartments than the ones the current design provides. This improvement point could deserve attention when the system's limitations are tackled in a further section.

Despite being an approximation based on empirical data and not on a theoretical justification, these results illustrate the mentioned complexity of drainage flow rate calculation because this rate does not have a linear relation with precipitation, with soil dynamics playing a crucial role. However, it provides valid data upon which the performance of the rest of the system can be supported.

The system is designed to combine the useful drainage flows from the three plots upon arriving at the pumping station. Water flow convergence depends on water properties and flow characteristics, such as temperature, turbulence, velocity, and chemical composition. Different flow rates can interfere with each other, canceling or reinforcing one another at different points, leading to areas with different flow rates. In this case, the water and flow properties are assumed to be almost equal. Since the water flows of 28 m^3/h travel, on average, a longer pipe distance, their impact will be higher on the combined flow. The simplest case would be perfectly even flow mixing, with each flow contributing equally to the combined flow. The combined flow value would be 98 m^3/h in this case. Considering that the 28 m^3/h flows have a higher influence, the result is multiplied by 2/3, resulting in a flow, at the input of the filtering system, of 65 m^3/h.

2) *Filtering System*

The performance of the filtering system is also complex. Three parts must be analyzed separately to calculate the losses within the filtering system: the sand filter, the pumping system, including pump and water pipes, and the activated carbon filter. Due to inaccurate information, some assumptions were made. Therefore, the calculated results are an estimate based on engineering principles used in fluid flow and filtration systems.

The sand filter is formed of three layers. The top layer has a high grain size and the highest porosity. It is assumed to be 40%. The intermediate layer has an intermediate grain size, and the bottom layer has the smallest grain size. Therefore, the porosity of these layers is respectively lower and lowest, assumed to be 35% and 30%. According to the top, intermediate, and bottom layer characteristics, head loss coefficients of respectively 10, 8, and 6 can be assumed. The pipe is a regular DN80 PVC pipe with an inner diameter of 80 mm. The results are presented in Table 4.

Table 4 - Parameters and results of the total head loss in the filtering system calculation

Parameters	***Values***
Flow Rate (Q) (m³/h)	65
Pipe Diameter (D) (mm)	80
Results	**Values**
Head Loss in Sand Filter (m)	0.634
Head Loss in Pumping System (m)	Approx. 0
Head Loss in Activated Carbon Filter (m)	0.156
Total Head Loss (m)	0.796

3) Pumping System

In what concerns the pumping system, and also taking into account the pump in between filters and the pump on the activated carbon filter output, it is composed of seven pumps. However, due to the intended yearly program of the ASR system and each pump's specific performance, these can be divided into two groups. The first group includes the pumps to be used during winter, which are the three drainage pumps and the two filtering pumps, and the second group includes the two well recovery pumps to be used during summer. Dividing the pumps into these two groups is justified by each season's different roles and functional requirements.

The first two groups are used primarily during the winter months, while the third group is used during the crop growth and irrigation season, whose duration varies according to each crop. The ideal design for the pumping system would consider constant flow for the pumps during limited periods, which start and end when a certain threshold is reached. However, the nonlinearity of the relation between precipitation and drainage flow rates greatly impacts predicting accurate flow rate values. For this reason, the pumping system will be dimensioned to be capable of providing the calculated flow rates during the entire winter season for the drainage and filtering pumps and the entire summer season for the recovery pumps.

a) Drainage pumps

For the drainage pumps, these should be, in reality, started from the moment the predefined water level is reached in the buffering compartment and should stop when the level is below this predefined threshold. The filter pumps should act only when there is a sufficient output flow rate from their respective output filter. Finally, the recovery pumps should start performing at the beginning of the crop growth season, predefined for each crop, and stop when the groundwater level rises to a depth in which sub-irrigation is possible through the roots of each crop. This can be achieved by using water level measurements and monitoring signals in the buffering, filter compartments, and at a certain aquifer depth. The aquifer development should also be closely monitored to verify that its dynamics unaffected. The ideal scenario would be that the farmer would receive a message on his smartphone at the moment at which he should manually turn the pump motors on and off upon identifying that a certain water level was reached. Certain apps are available for this purpose.

As seen before, the two pumps in the 90-hectare plots should be designed for a maximum capacity of 28 m³/h, while the drainage pump on the 139-hectare plot should have a maximum capacity of 43 m³/h. Considering flow convergence calculations already explained, and according to the head losses in each filter, the first filtering pump, situated between both filters, should be dimensioned for a maximum flow rate of 63 m³/h, while the second one, pumping directly into the injection wells, should provide 54 m³/h. This flow will reach a separation point along its pathway between both injection wells. Considering the proportion between well lengths, 2/3 of 54 m³/h, corresponding to 36 m³/h, should be injected in the 200-meter well, while 18 m³/h should be injected in the 100-meter well.

The drainage pumps (P1, P2, and P3) are installed in the buffering compartments at an approximate depth of 1 meter. The discharge path reaches its highest point at 2.5 meters in the pumping station. The water is then discharged in the sand filter at a height of 2 meters. The velocity in the input of the sand filter is calculated before and has a value of 3.48 m/s. The head losses by friction can be calculated using the Darcy-Weisbach equation shown in Equation 13.

b) Filtering Pumps

The filtering pumps were already dimensioned in the previous section related to the filtering system.

Summer season

Each crop has its specific growth period for the summer season, and the start of the recovery process should match the start of this period. The farmers should control this. The groundwater level at this point, the root depth, and the required irrigation rates all play a decisive role in defining the pumping requirements for the recovery pumps.

The three different crops all have relatively the same growth period, starting at the beginning of June and ending at the beginning of September. Each crop's specific irrigation requirements were calculated using the difference between measured summer precipitation and evaporation values in Texel during the analyzed period, multiplying these differences by each crop's evapotranspiration coefficient. This coefficient varies according to the crop's growth stage and is defined as the crop's evapotranspiration losses over a certain growth stage. If the evapotranspiration losses of the crops in each period can be compensated, then, in principle, the ASR system is effective. With the specific crop's requirements being different and considering the different areas of each plot, the needed recovery volumes are also different. The tables below present the figures related to these factors.

Table 5 - Estimated required irrigation flow for the existing crops

Estimated required flow [m³/h]	*Potatoes*	*Sugar beets*	*Livestock feeding grass*
Maximum	25.2	23.1	32.4
Average	10.9	10.2	15.0
Estimated total volume [m³]			
Growth season 2015	939	874	1287
Growth season 2016	1004	926	1380
Average	971	900	1334

According to these figures, it is then concluded that an average total of 1871 m³ must be extracted from the 200 m well, accounting for the necessities of both potatoes and sugar beets and that a total of 1334 m³ must be extracted from the 100 m well, accounting for the necessities of livestock feeding grass. This translates, on average, into a relatively constant hourly recovery flow rate of 11 m³/h, 10 m³/h, and 15 m³/h, respectively, for each crop during the growth season, as illustrated by the figure below. As the maximum flow values of 25 m³/h, 23 m³/h, and 32 m³/h are above the limit due to the expected aquifer injection rate, the recovery pumping system cannot be dimensioned taking into account these maximum values, so there is no guarantee that every day the evapotranspiration losses of the crops can be compensated for. This choice is made because, firstly, the environmental impact of damaging its few useful groundwater structures on the island is more important in the long run than maximizing agricultural production. Therefore, the recovery pumps will be chosen based on maximum flow rate capacities of 36 m³/h for the 200-meter well and 18 m³/h for the 100-meter well, values which are already explained. This translates into a constant flow rate of 18 m³/h for all crops. The ideal recovery flow rates, in mm/d, for each growth stage are also presented below.

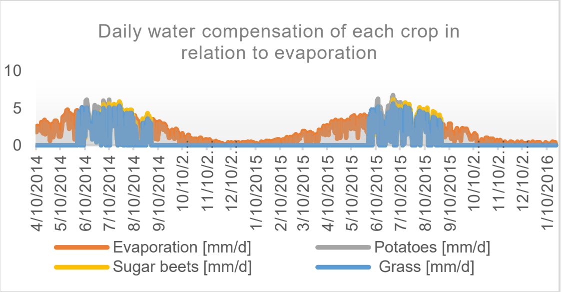

Figure 6 - Daily water compensation of each crop in relation to evaporation

c) Recovery pumps

Finally, each recovery pump was dimensioned for constant performance during the specific growth season of each crop, which will be presented ahead. Taking into account the allowed aquifer height variation rate and their maximum flow rate were defined, respectively, as 36 m³/h and 18 m³/h for the 200-meter and the 100-meter wells. This was defined because emptying the aquifer should ideally be done at lower or equal rates to filling to minimize the impact on its dynamic properties. In a further stage, it may be concluded that the crops require less water volume than the ones obtained using the estimated values above, and therefore, the required recovery pumps' flow rates may become lower.

An additional important aspect regarding the quality of the design is related to the way the infiltration volumes influence the hydraulic properties of the aquifer. Maximum height increase values for which the aquifer properties are not negatively affected are predefined by the experts in Acacia Water. A reasonable height increase is between 5 and 7 meters for the 200-meter well and 3 to 5 for the 100-meter well. According to the presented results, the expected water height increase on both aquifers is within these limits; therefore, no negative hydrological consequence is foreseen.

The second step is to calculate the Total Dynamic Head for each pump.

For the filtering pump between both filters (P4), the total dynamic head can be calculated considering only the static head, the friction head losses already calculated when describing the filtering system performance, and the velocity head. For the pump installed at the output of the activated carbon filter (P5), the total dynamic head is estimated considering a static head of 2 meters, corresponding to the maximum height of the pipes in the pumping station, with no elevation head, since the height difference between the pump and the discharge point for the wells is almost null, friction head losses and velocity head corresponding to the velocity at the pump output.

The recovery pumps (P6 and P7) have different total dynamic heads due to the geometric differences between both wells. For the 200-meter well, the static head is 10 meters, while for the 100-meter well, it is 6 meters. These are the depths at which these pumps are installed inside the well pipes. The elevation head is 9.2 meters and 5.2 meters, respectively, because the sub-irrigation point is at the drain depth of 0.8 m. The friction head losses are calculated as before, and the velocity corresponds to the required irrigation flow rates.

a) Pumping requirements overview

Finally, the estimated pumping requirements over time for each pump are obtained, taking into account each pump's efficiency, and it is then possible to calculate the required electric power for each pump. For visualization purposes, it seems beneficial to synthesize the explained information and expected pumping requirements in a table like Table 6 below.

This table presents the results for each pump's estimated maximum flow rate and total dynamic head, as well as the parameters that contribute to calculating these.

Table 6 - Pumping requirements of each pump

Pump ID	*P1*	*P2*	*P3*	*P4*	*P5*	*P6*	*P7*
Max. flow rate [m³/h]	28	28	43	63	54	36	18
TDH [m]	6.79	6.79	7.19	5.3	4.16	19.26	11.21

Based on the results shown in this table, it will be possible to select the correct pumps.

1) Design Limitations and Proposed Improvements

The previous section encountered some difficulties related to the system's design. These limitations are mostly related to water losses during the different processes or, on the other hand, with flow rates higher than what is reasonable for agricultural use water pumps currently available in the market or which seem economically reasonable for the purpose they are intended to satisfy.

The major identified losses were encountered in the drainage system due to the unpredictable nature of drainage, with estimated daily values within a very extended range, and in the filtering system design due to head losses.

The drainage system issues result in very inconsistent flow rates, with days when drainage is nonexistent and days when drainage flows are much higher than what a normal agricultural water pump has a capacity for. This aspect could be improved by over-dimensioning the buffering compartments that house the water pumps, allowing for a higher buffering volume. On the one hand, the recovered water volumes would increase, while on the other, the required flow rate from the pumps would be lower and spread more constantly over a longer period of time. Furthermore, this would not only improve the efficiency of both filters but also the efficiency of drainage. Lastly, scheduling the drainage pump operation periods would present a big advantage. This provides such additional advantages that it will be considered from now on, and the dimensioning of the new buffering compartments will now be introduced.

Along the plots run wastewater ditches, the ones into which the high salinity content water is discharged. These ditches have lengths of 300 meters and 150 meters, as shown in Figure 20. The solution for increasing the volume of the buffering compartments is to build new ones on top of the ditches. Two new buffering and storage volumes should, therefore, be built. One should be capable of buffering a maximum volume of 900 m³, while the other should be a buffer for a maximum of 700 m³. Both should have a height of 1.5 meters. The first buffering volume should be built on top of the 300-meter-long ditch, which runs aside the two 90-hectare plots and has a length of 300 meters and a width of 4.5 meters. The second one should be built on top of the 150-meter-long ditch, which runs aside from the 139-hectare plot, which has a length of 150 meters and a width of 3.5 meters. Despite not being built, these will be considered for further calculations and PV system design, as their existence largely facilitates operation and reduces the power input requirements of the PV panels.

Figure 7 - Top-view of the plots identifying the location of the lateral ditches where the installation of the reservoirs is proposed

The filtering system issues could be tackled by a better design and better relation with the input flow rate. One of the things that could be improved is the depth of the sand bed, which is too deep. A higher sand bed can reduce the head losses. Another factor that may lead to the calculated head losses is the use of different grain sizes. Uniform grain size can reduce head losses. However, in this case, a balance between minimizing head losses and being able to filter particles of different sizes must be taken into account, with a bigger focus on high filtering quality. Therefore, this aspect cannot be improved. The third factor that may lead to the increased head loss values in both filters, but majorly in the sand filter, is the sometimes too high input flow rate. This factor is difficult to tackle because it is a consequence of the drainage filter design and its dependence on uncertain natural factors such as precipitation and soil retention rates.

Two important measures to prevent future issues related to the identified challenges are installing monitoring and measuring tools and defining a regular cleaning and maintenance plan for all system parts. The first would include pressure valves on the input and output of the filters, communication, and record of infiltration and recovery flow rates, and monitoring of the aquifer growth using hydrological assessment tools presently well developed. The second includes periodically cleaning the drainage and piping, replacing the sand and activated carbon, cleaning the buffering compartments, and inspecting the pumps and their motors.

Apart from the already identified aspects, the system is expected to perform well and to be able to achieve its main objectives, which are, during winter, the extraction of reasonable volumes of useful drainage water, its filtration, and its posterior injection into the wells without damaging the aquifer, and during summer, the recovery of this water also without harm to the aquifer and providing the sufficient irrigation needs to the three studied crops.

C. Solar Pumping System

The second section, built upon the insights previously acquired, should focus on dimensioning a PV system that meets the pumping needs of the ASR efficiently and cost-effectively.

For this purpose, the required power for the water pumps, based on their flow rate and head requirements, is determined. Along with the expected pumping frequency and duration, this information serves as an estimate for the daily energy demand of the system.

Finally, to specify the chosen dimensions, number, and type of the PV system that ensures reliable operation of the water pumps during the complete ASR system cycle, as well as the inverter, battery (or justification for not using it), and wiring requirements, a solution that satisfies the expected system performance will be proposed.

1) Component Selection

After describing, assessing the design and relative limitations and challenges, and calculating the pumping needs for the complete ASR system to perform properly, the required power for the pumping system and the chosen pumps will now be defined.

Firstly, after all variables influencing the pumping needs were either calculated or estimated, as shown in Table 5, the necessary electric power for the pump motors, considering the ASR system as it is currently designed, is calculated and identified.

Grundfos was selected as the pump manufacturer for the intended pumps. This manufacturer provides tools that present options based on total dynamic head and flow rate. There is an extensive range of options for the requirements of each pumping stage. Grundfos also provides an app to monitor and control the pump operation directly from the owner's smartphone.

The pump possibilities mostly vary between each other based on the intended application, with different designs, construction, and materials used. Grundfos manufactures, amongst other types, submersible groundwater pumps and submersible wastewater pumps. Grundfos allows for auto-coupling with an integrated AC motor.

The manufacturer's support in selecting the best pump for each application mainly relies on consulting the performance curve (Flow/Head curve) of a certain pump model and identifying which point of operation, or duty point, provides the most similar to what was previously specified by the user, while being close to the BEP (Best Efficiency Point). It is usual to consider that, within a range of 70% to 120% of the BEP, the pump's hydraulic efficiency and operational reliability are not substantially reduced.

a) Drainage Pumps

The recommended pumps for drainage pumps P1, P2, and P3 are of the submersible wastewater type due to the low TDH and high flow required. According to the manufacturer, for the pumping requirements of pumps P1 and P2, the best solution is the pump model "UNILIFT AP35B.50.06.3V". These pumps require an input electrical power of 1 kW. For pump P3, the best solution is pump model "AP50B.50.08.3V", with an input power of 1.25 kW. The datasheet information of these pumps can be observed in Annex A.

b) Filtering Pumps

The choice for the filtering pumps P4 and P5 is the "SL1.50.65.11.2.1.502" submersible wastewater pump with an input power of 1.6 kW. The datasheet information of these pumps can be found in Annex B.

c) Recovery pumps

Regarding the recovery pumps, the choice for P6 is the "SP 60-2" submersible groundwater pump, with an input power of 4 kW. Finally, for pump P7, the choice is the submersible groundwater pump "SP 14-4", with a required input power of 1.1 kW. The datasheet information of both these pumps can be found in Annex C.

The total input power needed during winter is then the sum of the input power of the drainage and filtering pumps, 6.45 kW, and during summer, it is the sum of both recovery pumps, 5.1 kW. The fact that the required power from the solar PV system is higher in winter when irradiation values are lower might indicate, in advance, some added difficulties in making this system effective.

Table 7 - Selected pump model and respective rated power in kW

Pump ID	*P1*	*P2*	*P3*	*P4*	*P5*	*P6*	*P7*
Model	AP 35	AP 35	AP50	SL1.50.65	SL1.50.65	SP 60-2	SP 14-4
Rated power [kW]	1	1	1.25	1.6	1.6	4	1.1

d) Inverter

It is known that the inverter must provide a total of 6.45 kW to the pumps to satisfy both winter and summer needs. However, as the pumps P1 to P7 have different pumping and input power requirements, a more specific approach must be considered for each pump. However, inverters from the Grundfos series RSI (Renewable Solar Inverter) will be chosen due to their specific customization, making them compatible with the previously selected pumps.

The inverter choice is based on manufacturer guidance, in this case, Grundfos, which provides on their website a method to select the right inverter based on the total daily water pumping requirement and the month for which this operation is considered. For the winter pumps, the selected month is January because it has the lowest incident energy records. Therefore, the required PV output power differs, influencing the inverter choice. For summer months, and for the same reason, the calculation is based on April.

The pumps P1 and P2 have the same pumping requirements, so a single inverter can be used for these two pumps. The selected inverter is also from Grundfos and has the additional advantage of an integrated MPPT. The Inverter model is “RSI 3x380-440V IP66 4 kW 9.6A”. This inverter is also suitable for pump P3 despite this pump having slightly different requirements.

Pumps P4 and P5 will be connected to an inverter each. The model chosen is the same as for the drainage pumps, “RSI 3x380-440V IP66 4 kW 9.6A”.

Finally, pumps P6 and P7 require one 11 kW inverter each of the model “RSI 3x380-440V IP66 11 kW 23A”. The datasheet specifications of this inverter can be found in Annex D.

Each of these inverters is connected to their solar array. Therefore, 5 different solar arrays are needed. The estimated number of panels per array will be presented ahead.

Batteries

Due to the autonomous nature of this system, the isolated geography of the studied site, the reduced expertise or technical support available for the farmers, the often very high investment and maintenance costs, and taking into consideration that a reasonable number of PV panels can provide the sufficient power even in the worst irradiation scenario, it was decided that no battery pack will be included in the system.

Charge Controller and MPPT

The charge controller and MPPT are integrated into the selected inverter from the Grundfos RSI series.

e) PV Panels

The selected PV panels are Grundfos model “GF 270”. For each inverter used during winter, which are the inverters for pumps P1 to P5, 72 panels provide the required power. A total of 288 panels is needed. Each 72-panel array has an output of 19.44 kWp. When this value is compared to the required pump output power, the very low solar availability of the location is understood, with an average conversion efficiency between 10% (for the inverter of pumps P1 and P2) and 16% (for the inverters of pumps P4 and P5).

For the summer pumping requirements, calculated for April, for P6, an estimated 50 panels provide the necessary power to the inverter, with a peak power generation of 13.5 kWp. For P7, an additional 18 panels are necessary, with a peak output power of 4.86 kWp. A total of 68 panels are to be used during summer.

The total number of PV panels required to generate sufficient power is 360 panels. During summer, 292 are surplus. The “GF 270” datasheet can be found in Annex E.

2) Performance and Limitations

This section stands on the results previously presented to investigate the expected performance and related limitations for the complete solar pumping system. The ASR system can be divided into two periods: winter and summer. As the power requirements during winter are higher, and the solar pumping system was dimensioned, taking into account the requirements for this period, it will be analyzed in more detail than the summer period.

a) Pumping schedule

The pumping schedule is defined with a range from 8 hours per day to 16 hours per day, based on the expected or observed drainage flow rates and on the remaining reservoir capacity. The pumps are powered directly from the PV panels. During periods of solar unavailability, the buffering compartments can hold large volumes of water until the next period of sunlight. While the reservoirs are empty, free drainage flow should be allowed using a valve. Daily, the regular performance should be as described:

The reservoirs should be filled for the first eight hours of the day, from 00h00 to 08h00. From 08h00 to 16h00, or during the period of available sunlight, the PV system should operate. If there is sufficient water in the reservoir to allow for the average calculated flow rates of the drainage pumps, the PV system should provide sufficient power to the pumps to pump water from the reservoirs into the filtering system. On the contrary, if the reservoir is empty, the PV should feed the same power to the batteries. If the reservoirs’ total volumes are filled, the above-referred drainage valves should close, and water should be either retained on the soil or discharged to the ditch, according to the farmer’s choice. In the last 8 hours of the day, from 16h00 to 24h00, the farmer can choose between discharging the batteries, providing power for the pumps to partially or completely empty the reservoirs, or keeping the valve closed and the reservoir at the current volume.

For this process to be possible, the water level in the reservoirs and the drainage flow rates must be well monitored and communicated to the farmer to select the best option in each case.

b) Sizing and construction of the PV panels

The proposed design is installing the solar PV array on top of the buffering reservoirs, with a total available surface area of 1066 m². Covering the reservoirs with solar panels has diverse benefits that will be described ahead. So that both reservoirs can benefit from this design, a choice has been made regarding how many modules are installed on top of each reservoir. The choice to over-dimension the array is considered and may also have a series of advantages. The 900 m³ reservoir has a surface area of 600 m², 300 m length and 2 m width. 240 modules can be installed here, covering a total area of approximately 395 m². The 700 m³ reservoir has a surface area of 466 m², with the choice of installing 120 modules, covering an area of approximately 197 m².

c) Over-dimensioning and sun-tracking

Over-dimensioning the PV system can reveal benefits, for example, in case the modules’ efficiency is lower than expected due to high cloud coverage or sand and dust deposition on their surface, a factor that should be taken into account in a region like Texel, due to high wind and the proximity to the ocean. The extra modules also offer the possibility to modify the system, increasing its energy consumption in the future, which, in this case, seems reasonable due to the project's experimental nature. For this reason, it is proposed to acquire 360 panels instead of the 288 previously dimensioned.

Regarding the ability to track the sun's movement, it is proposed to build fixed solar panels at the optimal tilt angle of 35 degrees. This choice is due to the added complexity and costs of building a moving structure on top of the reservoirs and to the fact that all the inverters used can operate on the panels' MPP.

d) Reservoir Top Installation

Installing the PV system on top of the reservoirs has numerous advantages. Firstly, it is a smart solution regarding space use efficiency. The available area for installing the panels is limited for this project, with the most important thing for the farmers being non-interference with their crops' growth. With this choice, no further construction space is required than that needed for the reservoirs. Secondly, it provides additional benefits regarding water management, namely because covering the reserved water with the panels reduces evaporation losses and the effect on the surroundings, reducing, for example, the growth of algae and water contamination.

This solution also presents benefits for the PV system itself. The first one is that, especially during summer, the reserved water serves as a natural cooling system, and their efficiency can thus be improved, with cell temperature being one of the defining parameters for efficiency. The second one is that because the reservoirs are constructed close to all inverters and pumps of the ASR system, the expected electric losses in transmission cables are reduced, as well as the overall costs for cabling.

III. CONCLUSIONS

In conclusion, it was intended with this project to analyze an Aquifer Storage and Recovery (ASR) system as part of the Zoete Toekomst Texel project, with the primary objective of understanding the pumping requirements for such a system and examining the possibility of using photovoltaic (PV) panels to meet the pumps energy demand.

Throughout this document, an analysis of the constructed ASR system was carried out, firstly by analyzing the dimensions of the system and its composing parts and later by estimating the water demand patterns. The maximum average flow rate from each part of the system was estimated based on empirical data and theoretical information, and the required power input to the water pumps was obtained. With this information, the photovoltaic system was dimensioned to meet the maximum demand criteria, with 360 PV panels to be installed.

During winter, the 360 panels must be utilized to match the requirements of the 5 winter pumps, with a total energy consumption of 6.45 kW. During summer, 100 PV panels provide 5.1 kW to the two recovery pumps. These values are, based on the approximations and assumptions used during the project's development, sufficient to provide the required water for all crops without the need to resource any additional energy source.

The collaboration with Acacia Water was a very enriching experience, which provided valuable insights into the difference between theoretical knowledge and the practical constraints of a relatively large-scale project. The hands-on experience gained through this research has contributed to a clearer understanding of the challenges and complexities of studying geohydrology, water management technologies, and agricultural solar pumping systems.

Despite this study's good indication, conducting further informed research at a smaller scale and with a higher resource availability is essential. Aspects such as field testing, real data collection, and system performance monitoring, as well as a thorough economic analysis (in which the investment in such a complex system would be compared to the value return for the owners), which were not a part of this study, may reveal crucial in getting deeper insight on all the specificities of such a system and allow for a more accurate dimensioning and decision-making.

REFERENCES

1) *Kruisdijk, E. (2022). Re-use of drainage water for agriculture: Fate of agrochemicals and assessment of well clogging during aquifer storage and recovery. [Dissertation (TU Delft), Delft University of Technology].*
2) *García, A. M., García, I. F., Poyato, E. C., Montesinos, P., & Díaz, J. R. (2018). Coupling irrigation scheduling with solar energy production in a smart irrigation management system. Journal of Cleaner Production, 175, 670–682.*
3) *Pyne, D. (1995) Groundwater Recharge and Wells: A Guide to Aquifer Storage Recovery. Lewis Publishers, Florida, 376 p.*
4) *Carriço, J., Fernandes, J., Fernandes, C., & Branco, P. (2016). Technical and Economic Assessment of a 500W Autonomous Photovoltaic System with LiFePO4 Battery Storage. Conference on Sustainable Development of Energy, Water and Environment Systems.*
5) *Dhakal, M. P., Ali, A., Khan, M. Z., Wagle, N., Shah, G. M., Maqsood, M. M., & Ali, A. (2021). Agricultural water management challenges in the Hunza River Basin: Is a solar water pump an alternative option?*. Irrigation and Drainage, 70(4), 644–658.*
6) *Volk, M. (2013). Pump Characteristics and Applications, Third Edition. CRC Press.*