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Increasing food system sustainability using solar powered atmospheric water

Hanna Gustrin
MID SWEDEN UNIVERSITY
Ecotechnology and Sustainable Development

Examiner: Anders Jonsson, anders.jonsson@miun.se
Supervisor: Monica Odlare, monica.odlare@mdh.se
Author: Hanna Gustrin, hagu1905@student.miun.se
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Abstract

This study investigates the possibilities of applying water generated from the atmosphere for agricultural processes, particularly hydroponic systems. A solar powered, off-grid greenhouse system is proposed as a theoretical solution to food production, in areas affected by water scarcity. Two experiments are conducted with the purpose of testing atmospheric water quality and how it performs in a hydroponic setting. The plausibility of powering said greenhouse system using solar energy is investigated, considering several available solar technologies. Ultimately, the footprint area required to install enough capacity to power the system is discussed, and the potential site of such a system is modelled and visualized. The experiments concluded that atmospheric water is likely suitable for hydroponic use. The study also found that the footprint area required for the greenhouse system probably can be considered reasonable for certain applications, but more research and advances within solar power technology would be beneficial.

Key words

Hydroponics, distilled water, water scarcity, sustainable agriculture, climate analysis, humidity, solar power technology
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From production to consumption, there are many issues related to the food system of today. It is a highly unsustainable system, relying on methods conceived as efficient in terms of maximizing yield and profit. However, these methods can on the contrary decrease production efficiency as they contribute to less-than-ideal environmental conditions. Conventional agriculture requires exploitation of vast amounts of land, which on a local level can result in issues such as soil erosion and freshwater pollution. Current agricultural methods based on widespread monocultures are estimated to be the cause of 80% of deforestation (FAO, 2016) and 70% of freshwater use (FAO, 2017). Deforestation is a leading cause of climate change and the unsustainable use of freshwater resources are of growing concern. The use of water in agricultural processes is also highly energy intensive. This energy is not commonly supplied through renewable means, and the agricultural sector is a large emitter of greenhouse gases.

Another main issue is the globalization of the food system. The Global North demands constant availability of food items from all corners of the world, regardless of season. Food is transported major distances in an import/export cycle contributing to high levels of greenhouse gases in the atmosphere, as well as the inequality of distribution within the food system itself. On one end of the spectrum, some countries experience such an abundance of food that food waste globally has been identified as the third largest emitter of greenhouse gases (Swedish Food Agency, 2020). On the other end, almost one fourth of the world population was affected by food insecurity in 2018, and 47 million children under the age of five suffered from acute malnutrition in 2019 (UN Department of Economic and Social Affairs, 2021). The global society has been structured to elevate certain populations and exclude others, and food is one of the many representations of that. The issue of food inequality is essential, as it comes with strong moral and societal values (D’odorico et al., 2019).

The globalization of conventional agriculture represents a fragile food system, which coupled with the rapidly growing world population indicates the approaching of a breaking point. The current food system is not likely to sustain the 9.7 billion people projected to inhabit the planet by the year 2050 (UN Department of Economic and Social Affairs, 2019). World-wide systematic changes will be necessary, including an increase in sustainably sourced and locally seasonal foods. The United Nations Development Programme has identified a key entry point for making these changes to
be “investment in infrastructure and technology to improve agricultural productivity” (UNDP, 2021a). Technologies must be developed that improve productivity, reduce unsustainable use of natural resources, and utilize renewable energy sources such as solar power.

1.1 Background

The emergence of the AgTech sector (Agriculture Technology) has brought many innovative technologies with potential to help mitigate the issues related to the unsustainable food system. An example of such a technology is hydroponics. In hydroponics, crops are produced using a water-based nutrient solution instead of traditional soil (Bridgewood, 2003). One of the main responsibilities of soil in crop production is the delivery of sufficient levels of water, nutrients, and oxygen to the plant root. Using water to perform these services means issues often encountered when using soil can be avoided, such as for instance soil-transmittable diseases or pests, poor drainage or soil fertility, and topographical or geographical challenges (Khan, 2018). A hydroponic system can be placed outdoors, in greenhouses, or indoors with supplemental lighting in urban farms. Such a system allows for possibilities to harvest year-round, protect crops from extreme weather conditions, and minimize land exploitation while maximizing crop production. A higher degree of control over the crops can be achieved through hydroponics, which results in a more reliable harvest and the possibility for complete exclusion of pesticides (Khan, 2018). Hydroponic systems have also been shown to maximize efficiency in terms of freshwater and nutrient use, and show great potential to reduce waste while making balanced use of resources (Elvanidi et al, 2020).

Definition 1: A hydroponic system is in this study defined as a system of food production utilizing a water-based nutrient solution as a means to deliver nutrients to the crops, dispensed through the system at optimized time intervals depending on surrounding climate.

Hydroponics have gained a rather established foothold in the AgTech sector, and there are many commercially available solutions. Hydroponic systems have for instance become a common staple of indoor vertical farming, an industry that increasingly supplies leafy greens such as herbs and lettuces. Indoor vertical farming can be a solution to specific issues in specific locations, for example long periods of minimum
sunlight and colder temperatures in northern regions. However, other applications of hydroponics may need developing for other types of climates, in order to truly benefit more regions. Water is an essential input in hydroponics, and the way hydroponic systems are established today is not necessarily optimized for semiarid, subtropical, or desert climates. Most regions experiencing water scarcity due to agricultural activities are located in these types of climates, as is evident from Figure 1.

Figure 1: Contribution of the agriculture sector to the level of water stress, by basin, 2015 (FAO, 2020).

Over 40% of the world population are already affected by water scarcity today, a figure that is likely to rise with increased frequency of droughts due to global warming and climate change (UNDP, 2021b). A sustainable source of water would be necessary for hydroponics to be an applicable and sustainable solution to food production in the affected regions. One potential source of sustainable water, that has not yet been tested in crop production applications, is an innovative technology by a company named Drupps. This technology captures moisture present in the ambient air and transforms it into clean drinking water, offering an alternative source of freshwater called atmospheric water.

Definition 2: Atmospheric water is in this study defined as the ready-to-drink purified and mineralized water exiting a complete Drupps system as it is described in Figure 2.

1.1.1 The Drupps system

The Drupps-system uses fans to force ambient air through absorber units, where a hygroscopic fluid (FLOW) is used to capture H₂O-molecules present in the
atmosphere. From the absorber units, the FLOW diluted with water flows to an evaporator unit. The FLOW is there separated from the water and returned to the absorber unit in a closed loop. The distilled water exiting the evaporator unit continues through a purification and mineralization step before it leaves the system as available drinking water (Drupps, 2021). This system is highly scalable, and there is essentially no limit to the amount of water that can be produced as it simply depends on the number of absorbers used. A flow chart of the Drupps-system is presented in Figure 2, and this study will focus on the possibilities for agricultural application of the atmospheric water produced through this technology.

1.1.2 The greenhouse system

Theoretically, the composition of nutrients added to the water in the mineralization step could be altered to suit the needs of various crops, essentially preparing the exiting atmospheric water immediately for agricultural use. Sensors could be used to find the most appropriate fertilizer compositions for different species, and could automatically control the dilution of fertilizer in the nutrient solution based on plant growth stage etc. The output of the Drupps-system would then be a ready-to-use nutrient solution, which could be directly applied to irrigate a hydroponic system. The irrigation schedule would optimally be determined by plant transpiration rate, which can be measured using sensors and more or less complex models (Adeyemi et al., 2018).

The only input needed to run the Drupps-system is electricity, which implies the sustainability of the produced nutrient solution hinges upon the use of sustainably produced electricity. Consider a greenhouse where the ventilation system is replaced

![Diagram of the Drupps-system](image)
by a Drupps-system, powered by solar energy. The greenhouse climate could to an extent be controlled by the fans and absorber unit, while the produced nutrient solution could be applied directly to the plants. Since neither irrigation or cooling are necessary during periods of less solar irradiation and colder temperature, the greenhouse containing a Drupps-system and hydroponics could theoretically be powered solely by solar energy during the day – without the need for a large battery bank.

Definition 3: The greenhouse system is in this study defined as a stand-alone solar powered greenhouse, equipped with hydroponics producing crops and a Drupps-system producing the nutrient solution used in the hydroponics.

A greenhouse equipped with these systems and powered by solar means holds great potential to provide a sustainable and independent source of food. Particularly so for regions affected by water scarcity located in climates with high levels of humidity and solar irradiation. Atmospheric water could hold the key to bringing feasible AgTech solutions to these kinds of regions and could help alleviate some of the pressure from conventional agriculture on available freshwater sources. Depending on the scale of the Drupps-system, it could potentially provide additional drinking water beyond what is needed for the hydroponic farming taking place in the greenhouse. The combination and slight adaptation of these already available technologies could potentially help mitigate some of the challenges faced by the food system. By no means is there one simple solution to the problem of an unsustainable food system, and as previously mentioned more wide-spanning systematic changes will most likely be necessary as well. However, the greenhouse system described above could provide a starting point and would actively work towards the UN sustainable development goals # 2, 6, 9, 11, 12, 13 and 14: Zero hunger; Clean water and sanitation; Industry, innovation, and infrastructure; Sustainable cities and communities; Climate action; Life below water (UNDP, 2021c).

1.1.3 Problem formulation

There are a lot of uncertainties with the greenhouse system described above. Although the water produced by the Drupps-system has been certified food grade for drinking purposes by Swedish authorities, it has not yet been tested in agricultural – or hydroponic – applications. Furthermore, it is questionable whether this greenhouse system can become at all affordable for the relevant scale. Above all, it remains unclear
whether it would be possible to power the greenhouse with these subsystems using solar energy. The Drupps-system – particularly the evaporator unit – can be considered rather energy intensive. It is not given that solar energy is a feasible option to power the greenhouse system.

Powering the Drupps-system through solar means is the most critical aspect of the vision described above. If electricity must be present at the site of the greenhouse, the wide possibilities regarding geographical location will be limited, and it can no longer be considered a stand-alone solution. If fossil fuels were used, the greenhouse system would evidently not be considered sustainable. And finally, if renewable energy other than solar would be used, a large battery bank would most likely be necessary. Therefore, the integration of solar energy can be considered a key factor in the success of the greenhouse system.

1.2 Purpose of the thesis

The purpose of this study is to further investigate the possibility of powering the greenhouse system described in section 1.1.2 using solar energy. The scope of the study will be limited to investigating the possibility to power a small Drupps-system, dimensioned by a hypothetical water load, using solar energy. As a means of comparison between different solar power technologies, the study will focus on the total footprint area of the site.

*Definition 4: Footprint area is in this study defined as the total horizontal ground area which must be allocated for the technology.*

The scope will also include two initial experiments, which will be conducted to ensure atmospheric water is in fact suitable for hydroponic use. Following the experimental portion, the remainder of the study will focus solely on the solar energy aspect. The study aims to adhere to the objectives listed below, identified in the form of research questions.
1.2.1 Scientific objectives

Q1. Is the water produced through a Drupps-system suitable for hydroponic use?
Q2. How much water would a Drupps-system need to produce for the purpose of the greenhouse system described in section 1.1.2?
Q3. What would the energy input requirements of the Drupps-system be for application in the greenhouse system described in section 1.1.2?
Q4. What solar power technologies can be utilized to power a Drupps-system?
Q5. Would it be feasible, in terms of occupied footprint area, to supply the total amount of energy required for a Drupps-system through solar means?

2 Method

This study employs an experimental and analytical approach. A fundamental initial step to this study is the determination of whether the atmospheric water supplied by a Drupps-system can indeed be applied for agricultural use. Although the water quality of the ready-to-drink atmospheric water produced by Drupps can be considered equivalent to – or better than – Swedish tap water, the water has never been tested in crop production. This study will perform two practical experiments in order to determine the applicability of the water produced through a Drupps-system for hydroponic purposes, and thereby answering research question Q1.

Following the experimental portion of the study, a quantitative analysis will be performed in order to answer the remaining research questions. Important initial parameters will be determined through support of existing literature, providing the basis for determining the hypothetical water load and thus answering Q2. Following this step, power input requirements can be simulated using existing Drupps-models to answer Q3. Additional data regarding solar power alternatives will be retrieved through review of existing literature and the market. Finally, calculations will be performed to provide the answers to research questions Q4 and Q5.

2.1 Hydroponic experiments

Since the base ingredient of a hydroponic nutrient solution is water, where nutrients have been added, the quality of the water used becomes essential in the success of crop
production. Irrigation control, which is the process of determining the amount of nutrient solution that should be applied at what intervals, becomes a crucial aspect. Plants use water for internal processes such as photosynthesis and evapotranspiration, and once this water is removed from the plant root area it leaves behind mineral salts (Mavrogianopoulos, 2016). These salts can be present in the nutrient solution either due to the water used, or to the fertilizers applied. The level of available salts in the nutrient solution can be measured through electrical conductivity (EC) in units of dS/m or mS/cm. Although EC-levels may vary depending on plant maturity, temperature, and other parameters, it is commonly maintained in the ranges of 1 – 3 dS/m in hydroponic systems (Wortman, 2015). However, as the total concentration of salts increases in the root environment, it can have negative impacts by blocking the plants from absorbing necessary water, thus reducing the plant water intake (Mavrogianopoulos, 2016). Morano et al. (2017) found that a nutrient solution of 2.8 mS/cm produced higher yield and quality of crops than that of 3.1 mS/cm, which instead showed a reduced efficiency in water and nutrient uptake. Another study mentions that maximized yield of tomato in hydroponic systems can be achieved by keeping EC-levels in the range of 1.5 - 3.5 mS/cm (Lizarraga et al., 2003).

Considering these findings, an initial experiment was designed. In the evaporator unit of a Drupps-system, where the water is separated from the FLOW, the water is evaporated into vapor and then condensed back into liquid form. Ergo, the water is distilled before entering the purification and mineralization step, which also means it has a very low electrical conductivity. If the distilled water would be applicable for hydroponics, the current purification and mineralization step of the Drupps-system could essentially be bypassed, and nutrients could be added directly to the distilled water to create the nutrient solution.

**Definition 5:** Distilled Drupps-water is in this study defined as the distilled water exiting the evaporator unit of a Drupps-system, before entering the purification and mineralization step.

To test this theory and determine the applicability of the distilled Drupps-water for hydroponic use, two deep water culture (DWC) hydroponic systems were set up to grow lettuce. The DWC is a simple hydroponic system where the plant roots rest in a container of motion-less nutrient solution, not requiring pumps or other electronic equipment (Figure 3).
One of the DWC-systems was filled with regular tap water as provided in Uppsala, Sweden (location of experiment), and the other with distilled Drupps-water. Equal amounts of off-the-shelf nutrient mix (hydroponic nutrient solution by Nelson Garden) were added to both systems, the nutritional composition of which can be found in Table 1. All other parameters such as lighting, temperature and plant species were kept equivalent between the two systems. This experiment was not designed to match the pH and EC levels of the distilled water to those of the tap water, but rather to investigate the potential difference in outcome due to different water quality starting points. Therefore, 2 ml of nutrient solution was added per L of water added to either system, as per the bottle instructions.

Table 1: Composition of nutrients in the hydroponic nutrient solution manufactured by Nelson Garden, as per the information provided on the bottle.

<table>
<thead>
<tr>
<th>Element</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>S</th>
<th>B</th>
<th>Cu</th>
<th>Fe</th>
<th>Mn</th>
<th>Mo</th>
<th>Zn</th>
</tr>
</thead>
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<tr>
<td>%</td>
<td>4</td>
<td>0.7</td>
<td>3</td>
<td>1</td>
<td>0.3</td>
<td>0.3</td>
<td>0.02</td>
<td>0.005</td>
<td>0.05</td>
<td>0.02</td>
<td>0.003</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Lighting was applied post sprouting at 17 hours/day, and the distance of the lights to the plants was continually increased through the growth stages of the plants. Temperature, EC, and pH were continuously monitored over the next few weeks, with measurements taken at random times throughout the experiment. The visual aspects of the yield, such as growth and leaf color, were compared between the two systems by the end of the experiment. The experimental setup is presented in Figure 4 below.
Following the initial experiment testing the applicability of the distilled Drupps-water, another experiment was set up to test the applicability of the atmospheric water (Figure 5). The experimental set up remained constant between the two experiments, apart from a few factors: In the second experiment, the distilled Drupps-water was exchanged for atmospheric water, the plant species was green cabbage instead of lettuce, and the second experiment was conducted over a shorter time frame.

The results of these hydroponic experiments provide the data necessary to answer the first research question – Q1 – as defined in section 1.2.1 of this study.
2.2 Quantitative analysis

In order to answer the remaining research questions as defined by the scientific objectives in section 1.2.1, the power consumption of the greenhouse system must be determined. The total power required largely depends on the scale of the greenhouse system, which can be concluded through the definition of certain key parameters.

2.2.1 Key parameters

The scale of the greenhouse system mainly depends on water load and geographic location. The geographic location is of great importance as the amount of water produced by a Drupps-system largely depends on the humidity and temperature of the ambient air, which varies across different climate zones.

Definition 6: Water load is in this study defined as the target average amount of water the Drupps-system should produce in L/day, to satisfy the input requirements of the hydroponics in the greenhouse system. It depends on two variables: the size of the hydroponic system and the irrigation schedule.

The water load is thus defined by assigning a theoretical size and irrigation schedule to the hydroponics of the greenhouse system. There are many ways to determine the irrigation schedule of a hydroponic system, and timing of irrigation has been shown to have significant effects on both quality and quantity of crop yield (Rahman et al., 2017). Plant transpiration rate has been identified as the main parameter in designing a hydroponic irrigation schedule, and it can be modelled by a range of more or less complex dynamic models (Adeyemi et al., 2018). However, to increase the tangibility of this study, a real-life example will be used to determine the key parameters of water load and location.

In an Australian case study, Grewal et al. (2011) performed testing of water and nutrient use efficiency in an existing hydroponic greenhouse used for commercial crop production. Their experiment was performed in a 450 m² greenhouse with a plant density of 2.2 plants/m², belonging to a hydroponic farm in Londonderry, New South Wales, Australia. Londonderry is located in the south-east of Australia, in a region experiencing high levels of water stress due to agricultural activities (indicated by the red color on the map in Figure 1). In the Australian case study, two methods of hydroponic irrigation were compared in water and nutrient efficiency. The method ultimately determined to be more efficient – in which drainage water was recycled and
irrigation frequency depended on weather conditions – used a total of 188 L of water per plant during the 13-week-long experiment (Grewal et al., 2011).

From this information a hypothetical water load can be calculated, which would specifically satisfy the requirements of the greenhouse system discussed in the introduction of this study. The Australian case study describes a hydroponic system of relevant size placed in a greenhouse, using similar irrigation scheduling methods to those intended for the greenhouse system. Furthermore, the Australian case study was performed in a region characterized by conditions arguably suitable for the greenhouse system. Therefore, the water load and location of the Australian case study were adopted as the baseline for the present study, and the related calculations yield the answer to research question Q2.

2.2.2 Water production simulations

The scale of the Drupps-system is determined using the simulation tool developed and used by Drupps. A climate analysis is performed for the specified location, which gathers necessary information regarding the local conditions for atmospheric water generation. Through the simulation, the Drupps-system is then scaled to produce enough atmospheric water to meet the requirements specified by the water load.

The amount of atmospheric water that can be generated through a Drupps-system of a specified scale naturally depends on how many hours per day the system will be running. The simulation tool used by Drupps calculates the mean atmospheric water generation over 24 hours, assuming the system will in fact run all 24 hours. The idea behind the greenhouse system however, as described in the introduction, is that the system only should run while the plants need it – when there is solar irradiation present – thus reducing the need for a large battery bank. For the purpose of this study, the effective run time of the system will be assumed at 8 hours/day. As 8 hours is one third of 24 hours, the Drupps system will need over-dimensioning by a factor of three, while only running a third of the time.

The simulation tool yields the average atmospheric water generation due to the fact that actual production does vary according to the surrounding climate. Variables such as temperature and humidity, that change over time, determine how much water can be produced. The climate analysis for the location in question is therefore a necessary step in determining the scale of the Drupps-system. The climate analysis will thus be performed for the region in south-east Australia.
A visual representation of the climate simulation tool is presented in Figure 6 below. This graph has been developed by Drupps to show the amount of moisture an absorber unit theoretically can capture. The axes of the graph show the relative humidity and temperature of the incoming air (surrounding climate), and the color represents the amount of moisture that can be absorbed, in grams of water per kilogram of air passing through the absorber unit. Knowing how much moisture can be captured by one absorber unit, the number of units necessary to fulfill the desired water load can be calculated.

![Figure 6: The amount of moisture that can be captured by an absorber unit, in grams of water per kilogram of air passing through the unit, as it is modelled by Drupps.](image)

2.2.3 Power calculations

The power required to run the Drupps-system will be modeled using the simulation tool developed and used by Drupps, the results of which will provide the answer to research question Q3.

Definition 7: Total power requirement is in this study defined as the power required to run a Drupps-system of the scale defined by the key parameters. It is the sum of the power required by the evaporator unit and the power required by the absorber units.

The components of the absorber unit requiring electric input are two fans, one pump, and a variety of sensors. The average value of power necessary to run the absorber units is determined by the simulations.
The evaporation process can be performed using electricity, thermal energy, or a combination of the two. Today Drupps can commercially offer two types of evaporator units; electric and hybrid. Both evaporator units contain one evaporation process and one condensation process, yielding an output of distilled water. The electric evaporator unit utilizes a heat pump for the evaporation process, and is powered solely using electricity. The hybrid evaporator unit instead uses thermal energy (heat) from an external source, and performs the evaporation in a pressurized two-step process, thus requiring an input of thermal energy in combination with electricity. Pressurizing the system enables evaporation at lower temperatures, which means the steam exiting the first evaporation chamber is hot enough to induce evaporation in a second chamber, although at a lower temperature. This two-step process increases evaporation efficiency, ultimately yielding a higher output of water produced. Two simulations will in this study be performed, one to model a system utilizing a fully electric evaporator unit, and one to model a system utilizing a hybrid evaporator unit. These simulations will yield the total power requirement for each system, and ultimately provide the basis for comparison.

A review of existing literature and the relevant market will be performed in order to find solar power technologies with the potential to meet the total power requirement of the Drupps-system. Simulations of all plausible combinations of evaporator units and solar power equipment will yield the most efficient option, ultimately answering research questions Q4 and Q5.

3 Results

3.1 Hydroponic experiments

The data collected and recorded throughout the first hydroponic experiment – using distilled Drupps-water – is presented in Table 2. The first experiment was conducted over a period of 7 weeks, during which time the levels of pH, EC and temperature were measured at randomly selected times for each hydroponic system, as well as on the first and last days of the experiment. The initial values of the measurements taken of the two types of water - before the addition of nutrient solution into each system - are included in the table as well. The visual aspects of the final yield are presented in Figure 7.
Table 2: Recorded levels of pH, EC, and temperature throughout the first hydroponic experiment.

<table>
<thead>
<tr>
<th>Date</th>
<th>Distilled Drupps-water</th>
<th>Tap water</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH</td>
<td>EC (mS/cm)</td>
<td>T (˚C)</td>
</tr>
<tr>
<td>Initial values</td>
<td>5</td>
<td>0.72</td>
<td>20.8</td>
</tr>
<tr>
<td>1/2/2021</td>
<td>4.5</td>
<td>0.81</td>
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<td>10/2/2021</td>
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<td>0.88</td>
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<td>6</td>
<td>0.87</td>
<td>21.5</td>
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<td>5/3/2021</td>
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<td>0.85</td>
<td>22</td>
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<td>16/3/2021</td>
<td>5.5</td>
<td>0.79</td>
<td>21</td>
</tr>
<tr>
<td>23/3/2021</td>
<td>6</td>
<td>0.65</td>
<td>21</td>
</tr>
</tbody>
</table>

Figure 7: Results of the first hydroponic experiment.

The second experiment was conducted over a period of 3 weeks, during which the levels of pH, EC and temperature were measured at random times for each hydroponic system, as well as on the first and last days of the experiment. The recorded values (including the initial values of the water before the addition of nutrients) are presented in Table 3 below. Figure 8 shows the visual aspects of the results for the second experiment.
Table 3: Recorded levels of pH, EC, and temperature throughout the second hydroponic experiment.

<table>
<thead>
<tr>
<th>Date</th>
<th>Atmospheric water</th>
<th>Tap water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH</td>
<td>EC (mS/cm)</td>
</tr>
<tr>
<td>Initial values</td>
<td>5</td>
<td>0.1</td>
</tr>
<tr>
<td>30/4/2021</td>
<td>4.5</td>
<td>0.82</td>
</tr>
<tr>
<td>10/5/2021</td>
<td>6.5</td>
<td>0.96</td>
</tr>
<tr>
<td>13/5/2021</td>
<td>6.5</td>
<td>0.97</td>
</tr>
<tr>
<td>17/5/2021</td>
<td>7</td>
<td>0.97</td>
</tr>
<tr>
<td>21/5/2021</td>
<td>7</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Figure 8: Results of the second hydroponic experiment.

3.2 Quantitative analysis

This section details the results of the simulations run using the Drupps-models and the in-depth calculations performed.

3.2.1 Water load

The desired water load for the greenhouse system is an essential input value in the simulations using the Drupps-models. It was obtained using the values provided by the Australian case study by Grewal et al. (2011), detailed under key parameters of the methods section. Over 13 weeks a total of 188 L of water was used per plant, in a greenhouse with an area of 450 m² and plant density of 2.2 plants/m². The water load was thus calculated as follows.
\[(450 \, m^2) \cdot (2.2 \, \text{plants/m}^2) = 990 \, \text{plants}\]

\[(990 \, \text{plants}) \cdot (188 \, L/\text{plant}) = 186,120 \, L\]

\[
\frac{186,120 \, L}{13 \, \text{weeks}} = \frac{186,120 \, L}{91 \, \text{days}} \approx 2,000 \, L/\text{day}
\]

This value represents the water load expressed per 24 hours. However, as previously mentioned, the Drupps-system will only run for an average of 8 hours every day. Thus, the total water load value to be used is calculated through multiplication by a factor of three:

\[2,000 \, L/\text{day} \times 3 = 6,000 \, L/\text{day}\]

### 3.2.2 Climate analysis

From the simulations performed using the Drupps-models, conditions for atmospheric water generation at the specified location were determined as favorable. The detailed results of the climate analysis are presented in Figures 9 - 11 below. Figures 9 and 10 show the relative humidity and temperature, respectively, for the location in south-east Australia, plotted by the number of hours per year each value is experienced. Figure 11 presents the correlation between relative humidity and temperature, plotted for each hour of the year.

![Figure 9: Relative humidity in % for the location in south-east Australia, obtained through the climate analysis performed using the Drupps-models, plotted by the number of hours per year each value is experienced.](image)
3.2.3 System simulations

With the required input value of water load defined to 6 000 L/day, simulations for the location in south-east Australia were performed. Two simulations were performed, one for a Drupps-system using an electric evaporator unit, and one for a Drupps-system using a hybrid evaporator unit. The results of the two simulations are
presented numerically in Tables 4 and 5, and Figures 12 and 13 show the average water production on a monthly basis as obtained for the two simulations.

Table 4: Results of climate simulation of the electric system performed using the Drupps-models for south-east Australia, using the input value of 6 000 L/day for desired water load.

<table>
<thead>
<tr>
<th>Electric simulation</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum number of absorber units</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Avg. daily water production over year</td>
<td>4.95</td>
<td>m³/day</td>
</tr>
<tr>
<td>Max. daily water production</td>
<td>6</td>
<td>m³/day</td>
</tr>
<tr>
<td>Min. daily water production</td>
<td>3.4</td>
<td>m³/day</td>
</tr>
<tr>
<td>Avg. power performance, 3 absorber units</td>
<td>55</td>
<td>kWh/m³</td>
</tr>
<tr>
<td>Avg. power performance, electric evaporator unit</td>
<td>230</td>
<td>kWh/m³</td>
</tr>
</tbody>
</table>

Table 5: Results of climate simulation of the hybrid system performed using the Drupps-models for south-east Australia, using the input value of 6 000 L/day for desired water load.

<table>
<thead>
<tr>
<th>Hybrid simulation</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum number of absorber units</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Avg. daily water production over year</td>
<td>5.08</td>
<td>m³/day</td>
</tr>
<tr>
<td>Max. daily water production</td>
<td>6</td>
<td>m³/day</td>
</tr>
<tr>
<td>Min. daily water production</td>
<td>3.6</td>
<td>m³/day</td>
</tr>
<tr>
<td>Avg. power performance, 3 absorber units</td>
<td>62</td>
<td>kWh/m³</td>
</tr>
<tr>
<td>Avg. power performance, hybrid evaporator unit</td>
<td>26</td>
<td>kWh/m³</td>
</tr>
<tr>
<td>Avg. heat performance, hybrid evaporator unit</td>
<td>400</td>
<td>kWh/m³</td>
</tr>
</tbody>
</table>

Figure 12: Average water production in m³/day for each month, as obtained by the climate simulation performed for the electric evaporator unit, using the Drupps-models for south-east Australia and the input value of 6 000 L/day for desired water load.
Figure 13: Average water production in m³/day for each month, as obtained by the climate simulation performed for the hybrid evaporator unit, using the Drupps-models for south-east Australia and the input value of 6 000 L/day for desired water load.

Using the values obtained through the climate analysis, the average amount of electric energy necessary to run a Drupps-system containing three absorber units and an electric evaporator unit (E_E) - in the specified climate - can be calculated as follows:

\[ E_E = (55 + 230 \text{ kWh/m}^3)(4.95 \text{ m}^3/\text{day}) \approx 1411 \text{ kWh/day} \]

Similarly, the average amount of electric energy necessary to run a Drupps-system containing three absorber units and a hybrid evaporator unit (E_H-E) can be calculated:

\[ E_{H-E} = (62 + 26 \text{ kWh/m}^3)(5.08 \text{ m}^3/\text{day}) \approx 447 \text{ kWh/day} \]

As the hybrid evaporator requires both thermal and electric energy to run, the average amount of thermal energy necessary must also be calculated for the Drupps-system utilizing the thermal evaporator unit (E_H-TH):

\[ E_{H-TH} = (400 \text{ kWh/m}^3)(5.08 \text{ m}^3/\text{day}) \approx 2032 \text{ kWh/day} \]

It is evident from these calculations that the two alternative systems, both capable of reaching an average water production of 6 000 L/day, have different power input requirements. The fully electric Drupps-system requires an average of 1 411 kWh of electricity per day, while the hybrid Drupps-system requires an average of 447 kWh of electricity and 2 032 kWh of heat per day.
3.2.4 Solar power literature and market review

Evidently, a completely electric greenhouse system could be powered using regular solar panels; photo-voltaic (PV) panels. However, commercially available PV panels are known to have a rather low efficiency, usually between 10-25% (Geagea et al., 2018). Studies have shown the amount of solar irradiation a PV panel can transform into electricity to decrease by approximately 0.5% with each 1°C of panel temperature increase (Rakino et al., 2019). Although recent years have seen great progress in PV panel efficiency, there is value in exploring other alternatives that potentially could offer more efficient solutions for powering the greenhouse system of this study.

A generally more efficient alternative is to capture the solar irradiation as thermal energy, using solar collectors. There are promising technologies merging conventional solar panels with solar collectors, called photo-voltaic/thermal (PV/T) panels, where a fluid captures thermal energy while a PV layer simultaneously produces electricity (Buonomano et al., 2016). The electrical efficiency losses of the PV layer due to temperature are reduced, and maximum net energy efficiency values for PV/T-panels have been shown to reach over 60% (Leonzio, 2019).

Technologies have also emerged where thermal energy is captured by solar collectors specifically for use in steam generation. Such a technology could potentially be smoothly integrated with the evaporator unit of the Drupps-system, to provide the thermal energy necessary to run it using solar means. According to Liang et al. (2019), evaporation powered through solar means has unlocked new possibilities for clean water generation. Although not yet available commercially, experimental methods of enhancing solar evaporation performance have been developed approaching a thermal efficiency of 100% (Liang et al., 2019).

Considering these findings, there are essentially three plausible scenarios of how to power the evaporator unit using solar energy:

S1. A fully electric evaporator unit could be powered by electricity generated from solar PV panels.

S2. A hybrid evaporator unit could be powered by solar thermal energy and electricity, through PV/T-panels.

S3. A hybrid evaporator unit could be powered by solar thermal energy and electricity, through a combination of solar thermal collectors and solar PV panels.
An extensive review of the current market of solar power equipment for industrial use was conducted, comparing only reliable sources which may readily deliver equipment to Drupps. The solar PV panel found to provide the highest efficiency was a P-type mono-crystalline panel manufactured by the Chinese company JinKo Solar, currently the world’s largest manufacturer of solar panels (GlobalData, 2020). The JinKo panel is a so-called bifacial module, utilizing a transparent backsheet to increase the amount of solar irradiation that can be captured. With panel dimensions 2 274 x 1 134 x 35 mm, it provides a maximum efficiency of 26.42% (JinKo Solar, 2021). For the purpose of this study, this PV panel will be used for further calculations.

The market review concluded the most efficient commercially available PV/T panel (from reasonable suppliers) to be one from a French manufacturer named DualSun. The DualSun panel of dimensions 1 646 x 1 140 x 35 mm utilizes a photovoltaic front face and a thermal rear face, to yield an electrical efficiency of 20% and a thermal efficiency of 58.9% (DualSun, 2021). This PV/T panel will be used as a modelling example in further calculations of this study. An important note however, is that the output temperature of this PV/T panel is not known, but it appears to be less than 75.6°C (which is the stagnation temperature specified by the manufacturer). This may require some modifications to the hybrid evaporator unit, as it currently would prefer a temperature of approximately 120°C.

In the realm of solar thermal collectors, there are many available options, from liquid-based or air-based, to vacuum-tube technology. Many manufacturers can deliver solar thermal collectors for residential use with thermal efficiencies approaching 80% on effective areas not much bigger than regular PV panels. However, these collectors are not for industrial use - such as evaporation processes - as they do not provide an output of high enough temperature. Upon investigation of the solar thermal collector market, a front-runner manufacturer local to Sweden was discovered named Absolicon. This company develops and manufactures solar thermal collectors for industrial use that can deliver an output of steam of temperature and pressure up to 200°C and 20 bar. This company appears to provide the highest thermal efficiency for the output of the highest temperature available on the market. The efficiency - 76.6% - is based on the collector aperture area of 5.5 m2, while the outer dimensions of the collector are 5 508 x 1 094 x 343 mm (Absolicon, 2021a). The Absolicon collectors will be used for further calculations in this study.
3.2.5 Available solar irradiation

The average daily available solar irradiation varies depending on geographic location, and must therefore be estimated for the area in question. The farm in Londonderry, south-east Australia, was located at latitude 33.66°S and longitude 150.73°E (Grewal et al., 2011). The nearest solar exposure measurement station is located almost 4 km away, in Richmond at latitude 33.62°S and longitude 150.75°E. The 4 km of distance can be considered negligible, and for the purpose of this study the data collected at this station was used, as available online through the Australian Government, Bureau of Meteorology.

The annual mean daily global exposure for 2020 was recorded at 4.2 kWh/m² (Australian Bureau of Meteorology, 2021). This value is also called the global horizontal irradiance (GHI), and is the average total amount of irradiation received in 24 hours on a surface normal to the sun. A graph showing the daily GHI of the Londonderry location for the year 2020 is presented in Figure 14 below.

![Daily global horizontal irradiation for Londonderry, New South Wales, Australia, as measured throughout the year 2020](image)

Figure 14: Daily global horizontal irradiation for Londonderry, New South Wales, Australia, as measured throughout the year 2020 (Australian Bureau of Meteorology, 2021).

However, the amount of solar irradiation present on a surface depends largely on the tilt angle of said surface. The optimum tilt angle for capturing the incoming solar irradiation varies according to geographic location, and for the latitude and longitude of 33.62°S and 50.75°, respectively, the optimum tilt angle is estimated at 34° (Global Solar Atlas, 2021). At this particular angle, the average daily GHI is estimated to be 5.13 kWh/m² (Global Solar Atlas, 2021).
3.2.6 Scenario 1: PV panels

Powering the fully electric Drupps-system, $E_E = 1411 \text{ kWh/day}$ of electricity is necessary. With the average daily available solar irradiation of $5.13 \text{ kWh/m}^2/\text{day}$, the following theoretical effective PV panel area for panels with an efficiency of 100% ($A_{PV-100}$) would be necessary:

$$A_{PV-100} = \frac{1411 \text{ kWh/day}}{5.13 \text{ kWh/m}^2/\text{day}} \approx 275 \text{ m}^2$$

As previously discussed, solar PV panels are not 100% efficient. Accounting for the PV panel efficiency of 26.42%, the total required effective PV panel area ($A_{PV}$) can be calculated as:

$$A_{PV} = \frac{275 \text{ m}^2}{0.2642} \approx 1041 \text{ m}^2$$

With a panel height and width of $2274 \times 1134 \text{ mm}$ respectively - which is equivalent to a panel area of approximately $2.58 \text{ m}^2$ - the number of PV panels necessary to accommodate the electric Drupps-system can be determined:

$$\frac{1041 \text{ m}^2}{2.58 \text{ m}^2} \approx 404 \text{ PV panels}$$

At a panel tilt angle of $34^\circ$, one PV panel occupies the footprint area ($A_{PV-F}$) of:

$$A_{PV-F} = (1.134 \text{ m})[(2.274 \text{ m}) \cdot \cos(34^\circ)] \approx 2.14 \text{ m}^2$$

Depending on the arrangement of the PV panels, such as the number of rows and necessary spacing, varying values can be obtained for the total footprint area occupied by all 404 panels. The minimum necessary spacing between rows can be obtained geometrically according to Figure 15, considering shading from other rows. It is evident from this figure that the theoretical optimum distance between PV-panel rows ($S_{PV}$) is approximately $2743 \text{ mm}$.
Figure 15: Side view of geometric relationships between rows of solar PV panels of height 2.274 mm to incoming solar irradiation at a 34° tilt angle, resulting in a theoretical optimum panel row spacing of approximately 2.743 mm.

The spacing between the PV panels in each row will be considered negligible, as this value is unknown but could theoretically be assumed very small. An example layout can thus be created for S1 to obtain a value for total footprint area of PV panels, provided in section 3.2.9.

3.2.7 Scenario 2: PV/T panels

Powering the Drupps-system equipped with a hybrid evaporator requires both electricity ($E_{H-E} = 447 \text{ kWh/day}$) and thermal energy ($E_{H-TH} = 2032 \text{ kWh/day}$). For this scenario, two sets of calculations must be performed to reach the required effective PV/T area, both utilizing the value for daily available solar irradiation of 5.13 kWh/m²/day. Firstly, taking into account the electrical load and efficiency, the following theoretical PV/T panel area for panels with efficiency of 100% ($A_{PVT-100}$) would be necessary:

$$A_{PVT-E-100} = \frac{447 \text{ kWh/day}}{5.13 \text{ kWh/m}^2/\text{day}} \approx 87 \text{ m}^2$$

Applying the 20% electrical efficiency for the PV/T panels, the total required effective PV/T panel area ($A_{PVT-E}$) can be calculated as:

$$A_{PVT-E} = \frac{87 \text{ m}^2}{0.2} \approx 435 \text{ m}^2$$

Secondly, accounting for the thermal load and efficiency, similar calculations yield the theoretical and total required effective PV/T panel areas to be, respectively:
\[ A_{PVT-TH-100} = \frac{2032 \text{ kWh/day}}{5.13 \text{ kWh/m}^2/\text{day}} \approx 396 \text{ m}^2 \]
\[ A_{PVT-TH} = \frac{396 \text{ m}^2}{0.589} \approx 672 \text{ m}^2 \]

It is evident from these calculations that it requires a greater effective PV/T panel area to cover the larger thermal load of the evaporator. Therefore, the area of 672 m\(^2\) must be used in order to power the evaporator, which will also result in the generation of some excess electricity. The excess electricity that will be generated through this alternative can be calculated as follows:

\[
(672 - 435 \text{ m}^2)(0.2)(5.13 \text{ kWh/m}^2/\text{day}) \approx 243.16 \text{ kWh/day}
\]

With a panel height and width of 1646 x 1140 mm respectively - which is equivalent to a panel area of approximately 1.88 m\(^2\) - the number of PV/T panels necessary to accommodate the hybrid Drupps-system can be determined:

\[
\frac{672 \text{ m}^2}{1.88 \text{ m}^2} \approx 359 \text{ PV/T panels}
\]

At a panel tilt angle of 34°, one PV/T panel occupies the footprint area \(A_{PVT-F}\) of:

\[
A_{PVT-F} = (1.140 \text{ m})[(1.646 \text{ m}) \cdot \cos(34°)] \approx 1.56 \text{ m}^2
\]

As discussed in the previous section, the arrangement of the panels determine the total footprint area occupied by all 359 panels. The minimum necessary spacing between rows can be obtained geometrically according to Figure 16, yielding a theoretical optimum distance between PV/T-panel rows \(S_{PVT}\) of approximately 1986 mm.

Figure 16: Side view of geometric relationships between rows of solar PV/T panels of height 1646 mm to incoming solar irradiation at a 34° tilt angle, resulting in a theoretical optimum panel row spacing of approximately 1986 mm.
The spacing between the PV/T panels in each row will once more be considered negligible, as this value is unknown but could theoretically be assumed very small. An example layout can thus be created for S2 to obtain a value for total footprint area of PV/T panels, provided in section 3.2.9.

3.2.8 Scenario 3: Thermal collectors and PV panels

Using the online dimensioning tool provided by Absolicon, a footprint area of 2 156 m² would be necessary in the selected location to cover the power supply requirements of the hybrid evaporator unit, at an output temperature of 120°C (Absolicon, 2021b). This value is much more accurate than those obtained in the previous two sections, as they most likely take into consideration parameters such as piping, installation, and maintenance. However, for the purposes of the comparison made by this study, a certain consistency must be applied. Therefore, the theoretical footprint area is calculated below, following the reasoning of the previous two sections.

The theoretical area required to provide the thermal load of a hybrid evaporator unit, using solar thermal collectors of 100% efficiency ($A_{C-100}$) can be calculated similarly to that for PV/T panels as:

\[
A_{C-100} = \frac{2 032 \text{ kWh/day}}{5.13 \text{ kWh/m}^2/\text{day}} \approx 396 \text{ m}^2
\]

Applying the thermal efficiency of 76.6%, the the total required effective collector aperture area ($A_C$) can be calculated as:

\[
A_C = \frac{396 \text{ m}^2}{0.766} \approx 517 \text{ m}^2
\]

With the collector aperture area of 5.5 m², the total amount of collectors required to provide the thermal load can be calculated:

\[
\frac{517 \text{ m}^2}{5.5 \text{ m}^2} \approx 94 \text{ collectors}
\]

Considering the outer dimensions of each collector (5 508 x 1 094 mm), and the collector tilt angle of 34°, one collector occupies the footprint area ($A_{C-F}$) of:

\[
A_{C-F} = (5.508 \text{ m})[(1.094 \text{ m}) \cdot \cos(34°)] \approx 5 \text{ m}^2
\]

The minimum necessary spacing between rows can be obtained geometrically according to Figure 17, yielding a theoretical optimum distance between collector rows ($S_C$) of approximately 1 320 mm.
The spacing required between the collectors in each row is unknown, and will for the purposes of this study be assumed to be 200 mm. An example layout can thus be created for S3 to obtain a value for total footprint area of solar thermal collectors, provided in section 3.2.9.

Accompanying these collectors, the electrical load of the evaporator unit must be supplied by PV panels. The amount of PV panels necessary to supply the 447 kWh/day necessary can be calculated according to the calculations performed in section 3.2.6 of this study:

\[
\frac{447 \text{ kWh/day}}{5.13 \text{ kWh/m}^2/\text{day}} \approx 87 \text{ m}^2
\]

\[
\frac{87 \text{ m}^2}{0.2642} \approx 330 \text{ m}^2
\]

\[
\frac{330 \text{ m}^2}{2.58 \text{ m}^2} \approx 128 \text{ PV panels}
\]

The minimum necessary spacing between rows ($S_{\text{PV}}$) is 2743 mm, as obtained in section 3.2.6. The spacing between the PV panels in each row will once again be considered negligible. An example layout can thus be created for S3 to obtain a value for total footprint area of solar thermal collectors and PV panels, provided in section 3.2.9.

3.2.9 Site layouts

In order to provide perspective and a better visualization of the required footprint area in each scenario, potential site layouts were created. From these layouts, the total
footprint area allocated to each aspect of the greenhouse system was recorded. Common for all three scenarios is the footprint areas of the greenhouse and the Drupps-system. The greenhouse occupies an area \((A_G)\) of 450 m\(^2\), as provided by the Australian case study on which this study is based (Grewal et al., 2011). The Drupps-system in these drawings consists of a two-story platform, where the first story is occupied by the three absorber units and the second story is empty. Next to the platform, the evaporator unit and a water tank are placed. In Figure 18, the electric Drupps-system is displayed, and Figure 19 shows the hybrid Drupps-system.

Figure 18: Trimetric view of a Drupps-system of three absorber units and one electric evaporator unit.

Figure 19: Trimetric view of a Drupps-system of three absorber units and one hybrid evaporator unit.
The electric and hybrid evaporator units are of similar dimensions, and in both Drupps-systems the width and depth of the footprint occupied by the total system is approximately 13.5 and 8 m, respectively. This yields a total footprint area for the Drupps-system ($A_D$) of 108 m².

Part of the solar equipment could be installed on the empty second story of the Drupps-system platform, but for the purpose of area visualization all solar equipment has been placed on the ground in the scenario site layouts. The second story of the platform could also be extended to cover the evaporator unit and water tank, in order to provide more space for solar equipment.

The site layouts created for the three scenarios discussed in previous sections, using all values obtained throughout this study, are displayed in Figures 20 - 22. The PV panels in S1 are arranged in rows of width 52 m and depth 24 m, yielding a footprint area ($A_{PV-S1}$) of 1248 m². The PV/T panels in S2 are arranged in rows of width 52 m and depth 15 m, yielding a footprint area ($A_{PVT-S2}$) of 780 m². For S3 the solar thermal collectors are arranged in rows with width 69 m and depth 10 m, yielding a footprint area ($A_{C-S3}$) of 690 m². The PV panels incorporated in S3 are arranged in rows of width 37 m and depth 10 m, yielding a footprint area ($A_{PV-S3}$) of 370 m².

Figure 20: Site layout of S1: An electric Drupps-system powered by PV panels. The areas allocated for each component of this site are calculated as $A_D = 108$ m², $A_G = 450$ m², and $A_{PV-S1} = 1248$ m².
Figure 21: Site layout of S2: A hybrid Drupps-system powered by PV/T panels. The areas allocated for each component of this site are calculated as $A_D = 108 \, \text{m}^2$, $A_G = 450 \, \text{m}^2$, and $A_{\text{PV/T-S2}} = 780 \, \text{m}^2$.

Figure 22: Site layout of S3: A hybrid Drupps-system powered by solar thermal collectors and PV panels. The areas allocated for each component of this site are calculated as $A_D = 108 \, \text{m}^2$, $A_G = 450 \, \text{m}^2$, $A_{\text{C-S3}} = 690 \, \text{m}^2$, and $A_{\text{PV-S3}} = 370 \, \text{m}^2$.

4 Limitations

A couple of limiting factors that affected this study should be considered. The experimental portion of the study unfortunately coincided with an update of the purification and mineralization step in the available Drupps-system. The equipment
supplying the atmospheric water required for the second experiment was thus taken out of use for several months, halting atmospheric water production. Distilled Drupps-water could be obtained for the first experiment, but the second experiment was delayed several weeks awaiting finalization of the purification and mineralization step. Therefore, time was cut short for the second experiment, yielding somewhat ambiguous results as the plants were not allowed to reach maturity. It would have been preferable for the two experiments to maintain the same time frame, as they would have been more comparable.

Once the updated purification and mineralization step was installed, atmospheric water was produced and collected for the second experiment. However, at this point in time the mineralization equipment still lacked the CO₂-component, which provides the final increase of the atmospheric water pH-levels. Therefore, the pH-levels of the atmospheric water used in the second experiment were lower than intended. The water is pure and mineralized by UV sterilization and filtration through hydrocarbonate and active coal, but the low pH may have affected the plants. More importantly, the water used in the experiment might not be considered fully representative of the atmospheric water normally produced by the Drupps-system. This raises the question of whether the second experiment can be considered legitimate or not.

5 Discussion and conclusions

The scientific objectives of this study were defined in the format of research questions in order to structure the necessary data collection. The results display all information obtained throughout the study, but does not relate them to the individual research questions. Therefore, the results will here be discussed in terms of their relation to the relevant research question.

5.1 Question 1: Is atmospheric water suitable?

The first research question asked whether or not the water produced through a Drupps-system would be suitable for hydroponic use. From Figure 7, it is clear that the hydroponic system using distilled Drupps-water in the first experiment provided a lower yield than the hydroponic system using tap water. The tap water produced three large lettuce plants (one in every possible position resulting in a 100%
germination rate) while the distilled Drupps-water produced one medium lettuce plant (only 33.3% germination rate). Thereby, the distilled Drupps-water appears to not be suitable for hydroponic use. Arguably, these results highlight the importance of the purification and mineralization step of the Drupps-system. If the distilled water exiting the evaporator unit cannot be used directly, the purification and mineralization step is a key factor if the produced water is to be used for hydroponic use. It can thereby not be excluded from the Drupps-system, as initially theorized.

The results from the second experiment are not as straightforward and cannot be as easily interpreted as the plants did not have time to reach maturity. Another question mark presents itself as not all possible positions germinated for either system (66.6% germination rate in both hydroponic systems), which can be seen in Figure 8. It is not known what caused some of the seeds not to germinate, but it seems indicative that the atmospheric water has resulted in the same amount of germinated seeds as the tap water. The plants appear to have grown approximately the same amount in both systems, which could indicate that the atmospheric water can indeed be applied for hydroponic use. However, these results are not entirely reliable and it is questionable how legitimately they can be considered - since the atmospheric water used was not fully treated and therefore had a lower pH than would have been preferred. What is interesting however, is that the pH of the atmospheric water system steadily increased over the course of the second experiment. The plants appear to perform the task intended to be taken care of by the CO₂ component of the purification and mineralization step. Further research on this topic could yield interesting passive alternatives for treating the water produced in the Drupps-system.

Future research on the topic of using atmospheric water for hydroponic use is highly recommended. It would be beneficial to conduct future experiments using fully treated atmospheric water of the intended pH, as not all plant species can thrive in low pH levels.

5.2 Question 2: How much water is required?

The second research question demanded a value for the water load as described by Definition 6 in section 2.2.1. Evidently, the water load was determined at 2 000 L/day, or 6 000 L/day for a Drupps-system running 8 hours/day. The value of 2 000 L/day was obtained through a previously conducted experiment, spanning a 13 week long period in 2011. Cucumber was grown in the experiment, and water load may vary drastically
depending on species. Although this water load was obtained using drainage water reuse practices ultimately saving 33% of water used in the experiment (Grewal et al., 2011), approximately two thirds of the water used was still drained off - which is not very efficient. Arguably, hydroponic technology and methodology has developed a lot since 2011. Applying smart sensors and a more tailored irrigation schedule, the 2 000 L produced daily would most likely sustain more crops than those of the 450 m² greenhouse modeled. Further research is necessary to provide more accurate data, but a linear relationship can be predicted. If the 2 000 L/day is considered a starting value, 50% of savings in water use would double the greenhouse area possible to sustain, yielding 900 m². Although it is not possible to determine the exact size, it can be concluded that the size of the Drupps-system required to irrigate the 450 m² greenhouse most likely is smaller than that presented in this study.

5.3 Question 3: How much energy is required?

The third research question asked for the energy input requirements of the Drupps-system for application in the greenhouse system. It was concluded that powering a fully electric Drupps-system, \( E_E = 1 411 \text{ kWh/day} \) of electricity would be required, and that a hybrid Drupps-system would require both \( E_{H-E} = 447 \text{ kWh/day} \) of electricity and \( E_{H-TH} = 2 032 \text{ kWh/day} \) of thermal energy (heat). If, as previously mentioned, the water output of these systems would indeed be enough for a larger greenhouse area than originally intended, the energy input requirements would be lower.

Lower energy input requirements means less solar equipment would be necessary to power the greenhouse system, and the resulting system would be much more efficient than that described in this study. There are also other ways to optimize the Drupps-system to increase greenhouse system efficiency. The concentration of the FLOW is a parameter which can be altered to enhance its hygroscopic performance. If buffer tanks were dimensioned properly and added to the system, the FLOW could enter a multi-loop process in which the concentration could be used as a determining factor to ultimately increase the water absorption.

The majority of the energy required to run the Drupps-system is governed by the evaporator unit. There are however possibilities to enhance this energy-intensive process as well. The hybrid evaporator unit modelled in this study utilized a two-step evaporation process. This is only possible if the thermal energy input (heat) is hot enough and the system is pressurized to an optimized level. This process currently
required 120°C, but if the input temperature was increased to 200°C - as per the maximum output temperature of the Absolicon solar thermal collector - the evaporation process could be performed in three or even four steps. This would result in a small increase in input energy, and thereby a somewhat larger solar thermal collector footprint, but also a large increase of water production efficiency. With the available 200°C, the possibility of evaporation in several steps becomes an optimization factor, which should be investigated further.

5.4 Question 4: What technologies could be used?

The fourth research question, regarding what solar power technologies can be utilized to power a Drupps-system, was answered through an extensive review of existing literature and the market. It should be noted that although extensive, the review was not all-encompassing. For the market review, manufacturers were included based on apparent legitimacy and plausibility of actual delivery. With limited resources in sorting through manufacturers, there is a possibility that some alternatives were overlooked or excluded. Even so, the research question could be answered, and three solar power technologies were selected for further analysis; solar PV panels, solar PV/T panels, and solar thermal collectors.

The biggest problem with these results is that the output temperature of the PV/T panels is unknown. The only data provided by manufacturers regarding temperature was the so-called stagnation temperature at 75.6°C. The stagnation temperature is the maximum temperature the fluid can reach when the velocity of the fluid is zero, and this value is therefore likely much higher than the output temperature of the system. A comparison could be made with the Absolicon collector, where the stagnation temperature is specified as 460°C for a collector of maximum output temperature of 200°C. If the output temperature of the PV/T panels is indeed less than 75.6°C, it may not be possible to perform an evaporation process using this heat. Considering the ambient temperature of the surrounding climate on average is rather high (Figure 10), the difference between the two temperatures is likely not high enough to perform a second step of evaporation. This means a single-step evaporator must be used, which is less energy efficient and would require more solar equipment. If the output temperature of these PV/T panels is too low, evaporation may not be possible at all, completely excluding this type of solar equipment from the list of possibilities. Further research on this topic is recommended, but in the meantime, it can be concluded that
it would indeed be possible to power a Drupps-system using solar energy - either through solar PV panels, solar thermal collectors, or a combination of both.

Ultimately, it can be concluded with certainty that the greenhouse system described throughout this study would greatly benefit from advances in solar power technology efficiency. Harvesting more solar irradiation per unit area would unequivocally yield a higher energy output using less equipment, which evidently would be preferable. In the last decade great steps have been made within the field, increasing efficiency of solar power equipment. Manufacturers further pushing these limits in the future would be highly interesting for the greenhouse system described in this study.

5.5 Question 5: Is the footprint area reasonable?

The fifth and final research question can be interpreted as the ultimate findings of this study. Would it be feasible, in terms of occupied footprint area, to supply the total amount of energy required for a Drupps-system through solar means? The nature of this question sort of requires an interpretation to be made. Figures 20 - 22 show the final site layouts for each of the three scenarios concluded in this study. This layout could definitely be condensed, for instance by placing part of the solar equipment on the empty second story of the Drupps-system platform. More efficient use of space would decrease the necessary allocated area, optimizing land use. However, some assumptions were also made to simplify the calculation of the areas necessary for each scenario. Maximum efficiency of all solar equipment was used in all calculations, and the minimum area possible was calculated. No frames were taken into consideration for PV or PV/T panels, and no piping or maintenance requirements were included. With the current layout, it would not be possible to pass between rows equipped with a four-wheeler or tractor, and cleaning or other maintenance would be difficult if not even impossible. Evidently, the Absolicon field simulator provided an area requirement almost three times higher than that obtained through the theoretical calculations, and it is likely much more accurate. All solar equipment was also assumed to be mounted on sun-tracking equipment to increase efficiency, the movement of which probably increases the necessary distance between each panel/collector. More detailed investigations are recommended, taking into consideration more aspects of a physical installation.

Following the discussion in the previous section, the PV/T panel scenario could be excluded due to uncertainties, leaving S1 (electric Drupps-system powered by PV
panels) and S3 (hybrid Drupps-system powered by a combination of PV panels and thermal collectors). Whether these scenarios would be feasible or not probably depends on the conditions at hand for the customer. If the top priorities of the customer are water scarcity and greenhouse gas emissions, while investment capital and land use are non-issues, either of the two scenarios would be feasible. However, if a customer does not have the resources necessary in terms of land area, both scenarios can be immediately excluded.

If, as previously mentioned, the water produced through this size Drupps-system could sustain a larger production, the two scenarios would seem more appealing. They are not, however, unappealing as is. This study has concluded that there are at least two possible scenarios to power a Drupps-system using solar energy, and that there are many possibilities for optimization and efficiency increase. The area that must be allocated for the two scenarios can certainly be considered reasonable for at least some applications. One major benefit of this greenhouse system is that it is a completely off-grid solution. It can be placed essentially anywhere. Consider for instance the roof of an IKEA warehouse: A large, flat, and solar-exposed surface in immediate range of food consumption. If part of the food IKEA serves could be sourced hyper-locally in this manner, the cost and greenhouse gas emissions of global shipping would be reduced, while the area allocated for the greenhouse system would be negligible.

5.6 Overall conclusions

Ultimately, what is imperative is whether or not the greenhouse system suggested by this study may meaningfully impact food security, anthropogenic impingement, and use of natural resources. Most hydroponic systems currently used in indoor vertical farming are only capable of producing salad greens, which alone do not contain large enough amounts of calories to feed the world population. The greenhouse system described above provides the possibility for a much wider range of crops, as the size of the system can be scaled according to needs. It can do so while simultaneously reducing greenhouse gas emissions - both from agricultural processes and global shipments. The land use aspect remains uncertain, and further investigation is encouraged to ensure the greenhouse system can be used as a means to relieve the pressure on forests and other important lands. Most importantly, this study concludes that the greenhouse system concept investigated has the potential to become a powerful tool in mitigating issues of freshwater use in the agriculture sector.
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