D1.6

Demonstrator results including monitoring data

THEGREEFA

Thermochemical fluids in greenhouse farming

DISCLAIMER

This project has received funding from the European Union's Horizon 2020 research and innovation Programme under grant agreement 101000801.

Document references

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[1] PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

Document history

V	Date	Beneficiary	Short description of contents and/or changes
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Executive Public Summary

The project demonstrators in Switzerland and Tunis were aimed at providing experimental findings and approval of different solutions for using open thermo-chemical technology in greenhouse agriculture. Greenhouse cultivation is an intensive form of food production with very high yields per surface. However, growing food in greenhouses is relatively energy intensive, due to the demand of heating during the cold season, dehumidification requirements and in relation to the growing use of seawater desalination for irrigation purposes. While water consumption is generally lower (in relation t of product/ha) compared to the open field, the high profitability of this cultivation method leads to high water consumption and over-use of groundwater resources in regions, where it is mostly established. These are regions with specific climatic and environmental benefits where the agri-business developed subventions for water and energy. A side effect is, that new technologies and environmental solutions are not automatically adopted by the farmers but must be developed and approved by research activities like in „TheGreefa". The results from the demonstrator in Zürich already approved an increase of energy efficiency for heating and humidity control of over 50% and showed solutions for the regeneration of thermo-chemical fluids under use of solar energy and residual heat. The Demonstrator in Tunis started at a much lower TRL level but the results achieved provide a clear approval of the system of day/night storage of heat and cool and the use of absorber technology for uptake and storage of water from humid greenhouse air. Further advances relate to the use of low-cost material and use of locally available resources, like the Liquid Desiccant taken from Tunisian Salinas, which until now is a residue from the table salt production.

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1 Introduction

The relation between the two demonstrators built in this project and the programme goals of reduced energy consumption in agriculture can be found in the areas of thermal energy requirements for greenhouse space heating, humidity control as well as in the field of seawater desalination. The area of open absorption technology using Thermo-Chemical Fluids (TCF), usually also named "Liquid Desiccants" can address these quite different topics and areas of energy consumption in an adequate way.
The aim of this document is not to present and explain the absorption technology for humidity and temperature air control in the greenhouse. For this scope, please refer to the deliverables D 1.1 "Concept for a partial automation for greenhouse air conditioning in temperate, warm summer climate zone "and D 1.4. "Tunis Greenhouse".

1.1 Swiss Demonstrator for continental regions

The main goal of the system installed in the Swiss greenhouse is to demonstrate its automatic operation for both internal climate regulation and TCF management. To achieve this, the system has been continuously operational for over a year, with the exception of planned and unplanned shutdowns. Using the measured data, it was also possible to compare the performance of TheGreefa system to that of a conventional greenhouse. Finally, the evaluation included assessing the implications in terms of storage volume and solar panel requirements for having an on-site self-sufficient system for TCF production.

1.2 Tunisian Demonstrator for Mediterranean regions

The main objective of the experimental work in this section of the project is to assess the performance of a Brine-based Liquid Desiccant System (LDAS), used for air conditioning in a closed greenhouse. This means cultivating crops in an (almost) closed atmosphere. The investigations focus on evaluating the efficiency of the LDAS in creating greenhouse's balanced and controlled climate, fostering optimal conditions for plant growth under Tunisian climate conditions, all while reducing the overall energy consumption. The control of the climate in a closed atmosphere is quite challenging, especially in an area as hot as Tunisia. However, solving the climate control issues is a precaution for other benefits of the system like (1) the possibility to grow crops at highly increased CO2 levels in the range of 1000-2000ppm. This is not possible economically in an open or semi-open greenhouse, as most of the carbon dioxide supplied would get lost in the aeration. (2) In a closed greenhouse, water can be cycled, as air humidity does not (or only merely) get lost to the environment. It is then possible to recycle water by collecting condensed water droplets from the inner surface of the roof, due to the systems water and thermal energy storage system, this will mainly be achieved during the night operation.

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2 Swiss demonstrator for continental regions

This chapter presents the demonstration phase of the technology of TheGreefa performed in the Swiss demonstrator, a greenhouse located by Zurich and operated by Meyer Orchideen AG, partner of the project TheGreefa.

The scope is not to described in detail the demonstrator facility. For that description, please refer to the deliverable D1.3 "Concept for a fully automated control system and operating manual".

The greenhouses are a perfect application to test the absorption technology for the temperature and humidity control: the plants release a large amount of humidity through transpiration, which requires to be removed. The thermochemical fluids (TCF) remove by an absorption process this excess of humidity production and useful heat is released at the same time of the absoprtion (transformation of latent heat in sensible heat). A further advantage of the sorptive air condition in the greenhouse, is that it is not any more necessary to exchange fresh air with the extern to control the humidity, that means that the thermal energy losses can strongly be reduced (Figure 1).

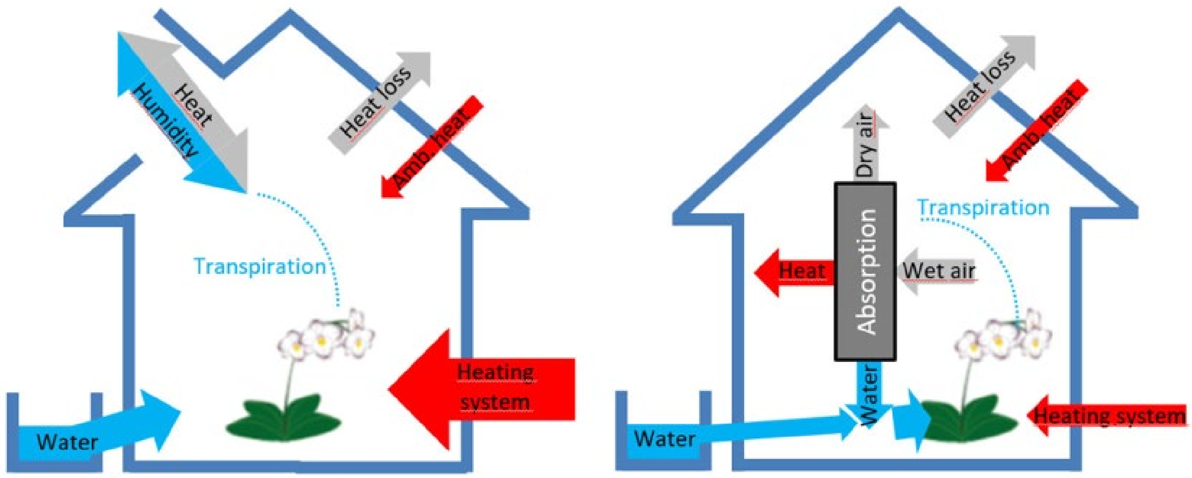

Figure 1: Energy and mass flow in a greenhouse without an active humidity control (left) and a greenhouse with TCF air conditioning as in the TheGreefa (right)

The ZHAW tested this technology in the greenhouse of Meyer Orchideen AG located closed by Zürich, in Switzerland. Furthermore, a new air distribution system has been developed, where the conditioned air is injected directly below the crops (Figure 2, left).

The system is also used for dehumidification and cooling. In this case, the combination with the evaporation cooling could be necessary: excess humidity is removed in the absorber, here the air temperature is cooled by the cooling water. In case a lower air temperature is required, water is sprayed under the flowers and the evaporation of the water drops down the temperature of the dry air coming from the absorber (Figure 2, right).

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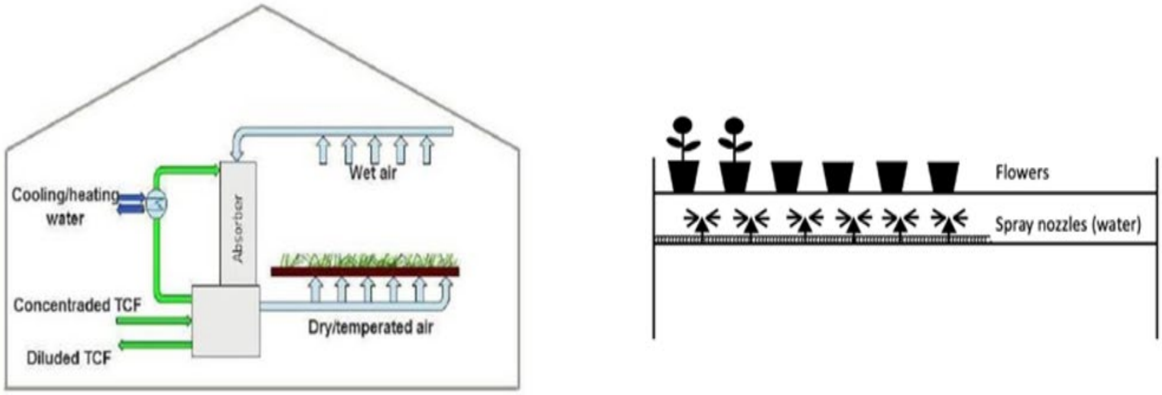

Figure 2: Schema of the conditioning system (left), Evaporative cooling installed on the tables (right)

The greenhouse No. 12 of Meyer Orchideen AG has been selected as demonstrator (Figure 3). The greenhouse has a surface of 600m^2 and there are 28 planting tables. The orchids in this greenhouse are in the flowering stage, which requires a constant indoor climate with a temperature of 18 to 22°C and a relative humidity between 50% and 70%.

Figure 3: Greenhouse No. 12 of Meyer Orchideen AG. One of the 9 absorbers in market in green (right). The orange pipes on the top are the air suction pipe system. The new structure of table is visible (white wall with blue edge around the crops)

The sorptive greenhouse air-conditioning system consists of nine absorbers, one desorber, four buffer storage tanks plus the balance of plant. The absorbers are installed inside the greenhouse, each of them supplies conditioned air to a minimum of 2 up to a maximum of 4 tables. The tables are enveloped in a wall to maintain the conditioned air directly on the crops. The desorber and the four storages are located outside the greenhouse in a wood container (Figure 4).

The system is connected to water circuit of the heating and cooling system.

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Figure 4: Desorber (left) and TCF storage tanks (right) in the container outside the greenhouse.

2.1 Experimental setup

The measurement points used to monitor and operate the plant were presented in deliverable D1.1, Chapter 5, and their setup in the control system was illustrated in deliverable D1.3. Figure 5 and Figure 6 show an enlarged view of the P&ID that illustrates the desorber and a single absorber. The values of the measurement points marked with an R are recorded data.

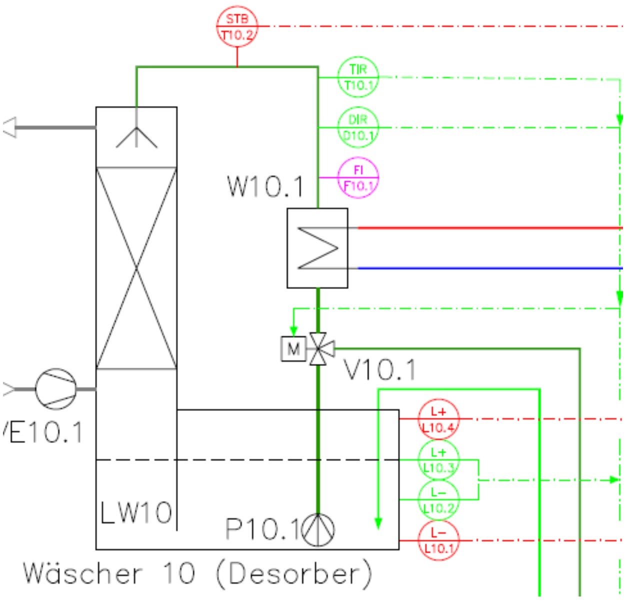

Figure 5: zoom of the P&ID on desorber

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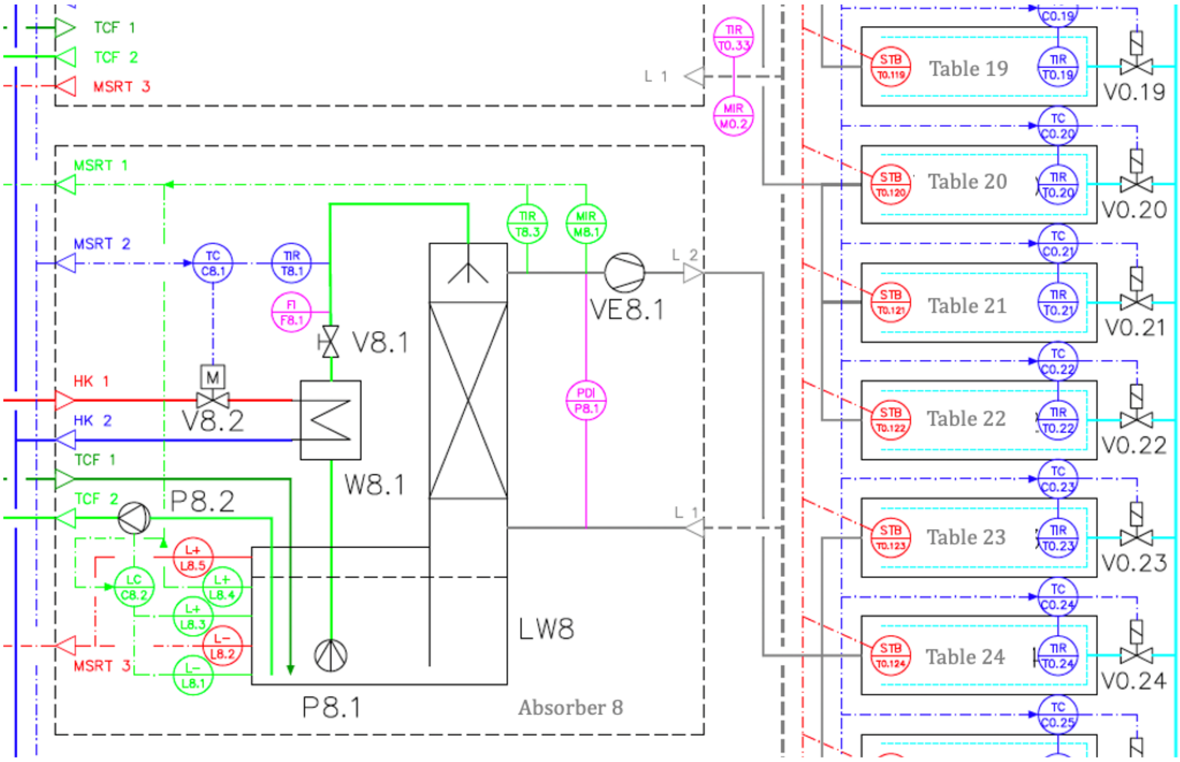

Figure 6: zoom of the P&ID on absorber nr. 9

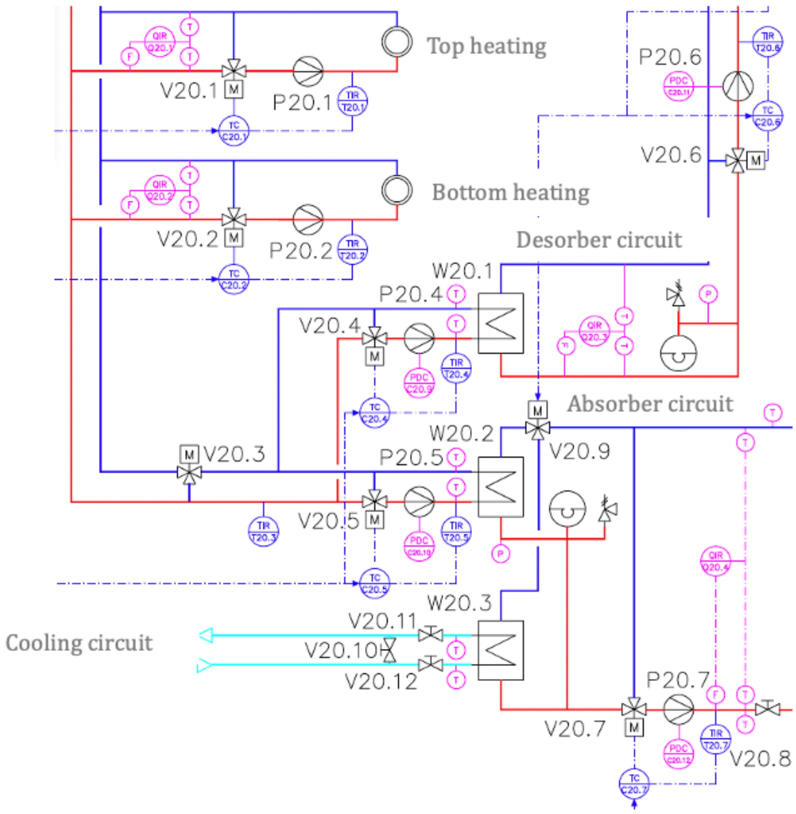

Figure 7: zoom of the P&ID on heat meters

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The significant data for this report recorded around the desorber are:

- T10.1, the TCF inlet temperature
- D10.1, the TCF inlet density
- L10.3, the liquid level in the sump

The significant data for this report recorded inside the greenhouse are:

- T0.x, the air temperature of the table x
- T0.31 equivalent to T0.33, the greenhouse temperature
- Mx.1. the relative humidity of the air leaving the absorber x

Furthermore, the operating hours or the activation times of the following components are recorded

- Vx.1, the ventilator of the absorber x
- Px.1, the recirculation pump of the absorber x
- V0.x, the valve for the evaporative cooling of the table x
- V10.1, the valve starting the operation of the desorber

While the temperature and humidity data are used to monitor and control the plant's operation, the thermal energy consumption is used to evaluate the performance of the plant. The energy is recorded by heat meters. An excerpt from the P&ID shows their locations (Figure 8)

- Q20.1 for the top heating
- Q20.2 for the bottom heating
- Q20.3 for the TCF regeneration
- Q20.4 for TCF temperature control in the absorbers. The Q20.4 distinguishes the energy used for heating and that for cooling.

The plant was handed over to the greenhouse operator Meyer Orchideen AG in July 2022. While the demonstrator was expected to be ready for the demonstration phase within a year, this phase could not commence immediately due to the need for further optimizations identified during initial operations.

The first issue involved the existing heating system, which remained active even during the cooling mode. This issue, detailed in Deliverable 1.2, Section 4, took some time to be diagnosed and resolved. It was found that the valves in the existing system could not close completely.

At the beginning of 2023, the plant TheGreefa definitively entered the demonstration phase without interruptions, aside from planned and unplanned shutdowns. The demonstrator remained operational until the end of the project in May 2024. The evaluation period spans 12 months, from February 2023 to February 2024. During this period (Figure 8), there were 115 days of downtime, primarily due to technical issues that were subsequently resolved. Some interruptions were due to planned activities, such as the installation of the nozzle's final configuration for evaporative cooling in May 2023 and operational optimization in July 2023.

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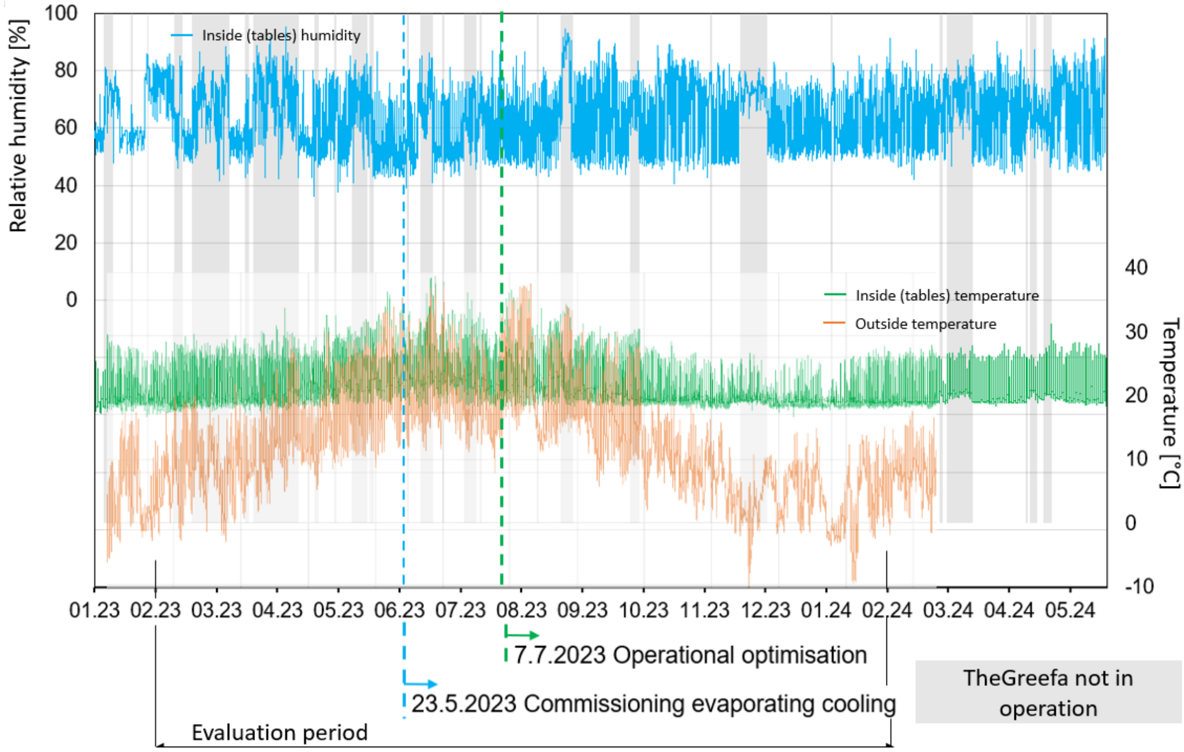

Figure 8: Overview of the Operating Period of the Swiss demonstrator

2.2 Measurements and Interpretation of the results

The following sections address the greenhouse as a whole and the single absorber is not any more analysed. Please refer to Deliverable 1.2, Section 4 for the performance and operation of the single absorbers. Deliverable 1.2 discussed how the outlet temperature of each single absorber is maintained at a constant set value, while the humidity is kept within an acceptable range. The humidity consistently increases from a minimum value when using a concentrated TCF until it reaches the maximum permissible limit. This indicates that the TCF becomes too diluted and needs replacement.

2.2.1 Temperature and humidity

During the demonstration phase, the humidity inside the greenhouse as well as the air temperature inside and outside the greenhouse were recorded continuously, also in case of outage of TheGreefa. The recording is reported in Figure 8.

The relative humidity remains in a range between 45% and 80%. There are some picks for short time, they could be due to the outage of the absorber or also to the watering of the greenhouse. The temperature above the tables does not follow the external temperature, nor does it remain constant at a set value as it does immediately at the absorber's outlet (refer to Deliverable 1.2). Throughout the year, the nighttime temperature is maintained around 18°C, while during sunny hours, there can be significant temperature spikes for short periods.

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Even if the temperature does not remain constant, this is not an issue for the greenhouse operator. The crops do not suffer for high-temperature peaks. In fact, the peaks were measured in the greenhouse and not directly around the crops, where the temperature stays lower (Figure 9). This is because the evaporative cooling is applied directly to the tables and the cooling effect is there where is needed. The temperature difference between the air of the greenhouse and the air in contact with the crops could be slightly less than 10°C in a typical summer day. The relative humidity increases constantly and as soon as exceeds the maximum value, the diluted TCF is replaced by concentrated TCF. To maximise the effect of the evaporating cooling, the TCF was also cooled down by ground water, the required cooling energy for the entire greenhouse is reported also in the Figure 9.

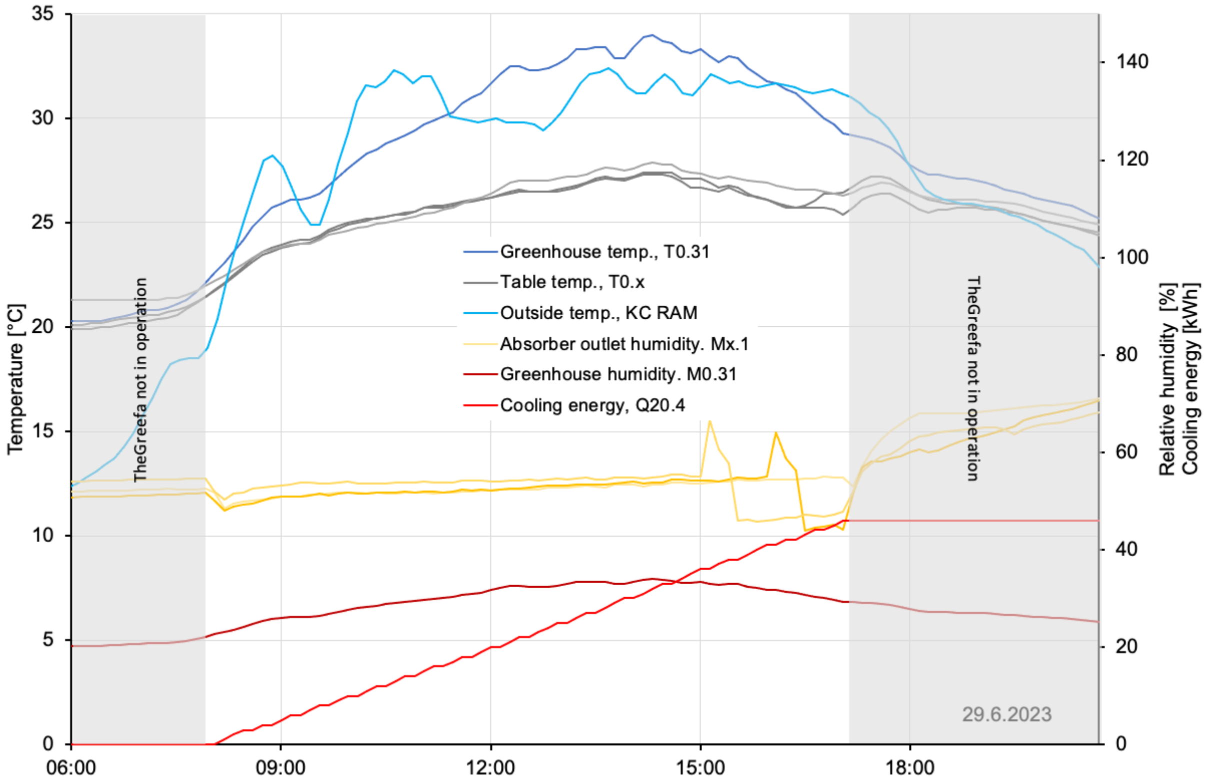

Figure 9: recorded data in a typical summer day

In winter the situation is reverse (Figure 10). TheGreefa is in operation during the night to heat the greenhouse and there is no difference between the air temperature of the greenhouse and the temperature above the table. The de-humification effect of TheGreefa is very well shown: TheGreefa maintains a constant relative humidity in the night even if the temperature decreases. The heating effect of TheGreefa is supported by the traditional heating system. During the day, when there is solar radiation, heating is not required and TheGreefa is not in operation.

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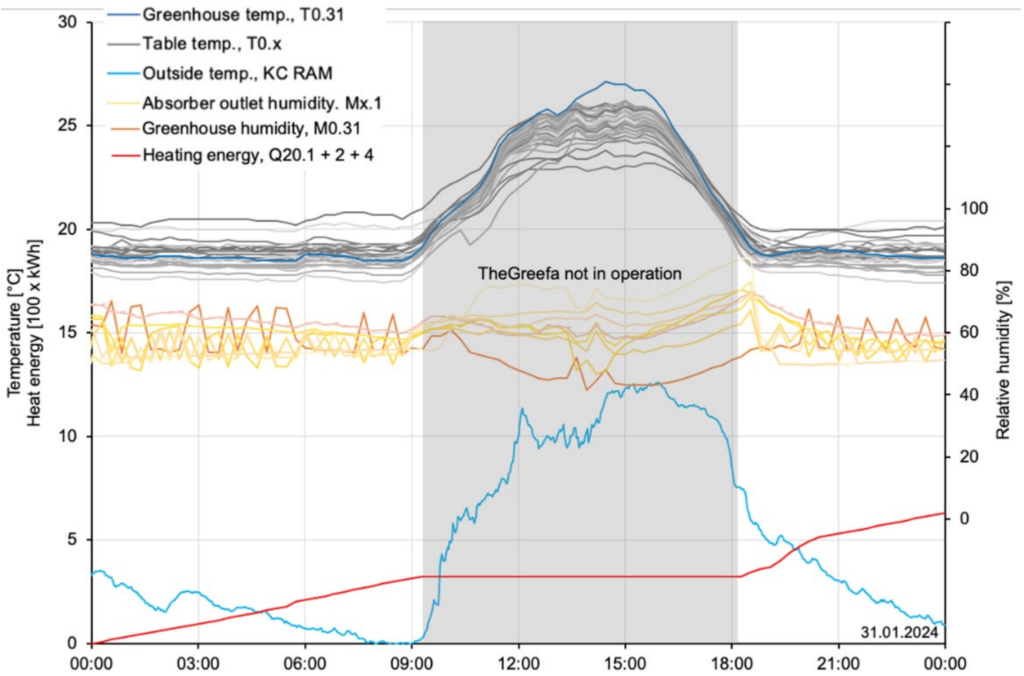

Figure 10: recorded data in a typical winter day

2.2.2 Consumptions in the demonstrator greenhouse

As presented in the previous section, the temperature and the humidity could be maintained inside the required range during the entire demonstration phase. This happen also when TheGreefa was not in operation; in this case the fully automatic control system switched to the traditional system and the greenhouse is operated as before the installation of TheGreefa.

The consumptions of the system are now analyzed.

Thermal energy consumption

Thermal energy is supplied for heating and cooling.

Heating

In the heating mode, warm water supports the absorption system, if necessary, by heating the TCF of each single absorber in the heat exchanger Wx.1 (Figure 6) and/or providing additional energy in the top and bottom heating system through the heat exchangers. This heat of the warm water is produced by the ground-water heat pump or/and by wood boiler installed in the Meyer Orchideen AG.

The energy consumption for heating over one year is reported in Figure 11. It is the sum of the energy recorded by the heat meters (Figure 7)

- Q20.1 for the top heating
- Q20.2 for the bottom heating and
- Q20.4 for the absorber circuit.

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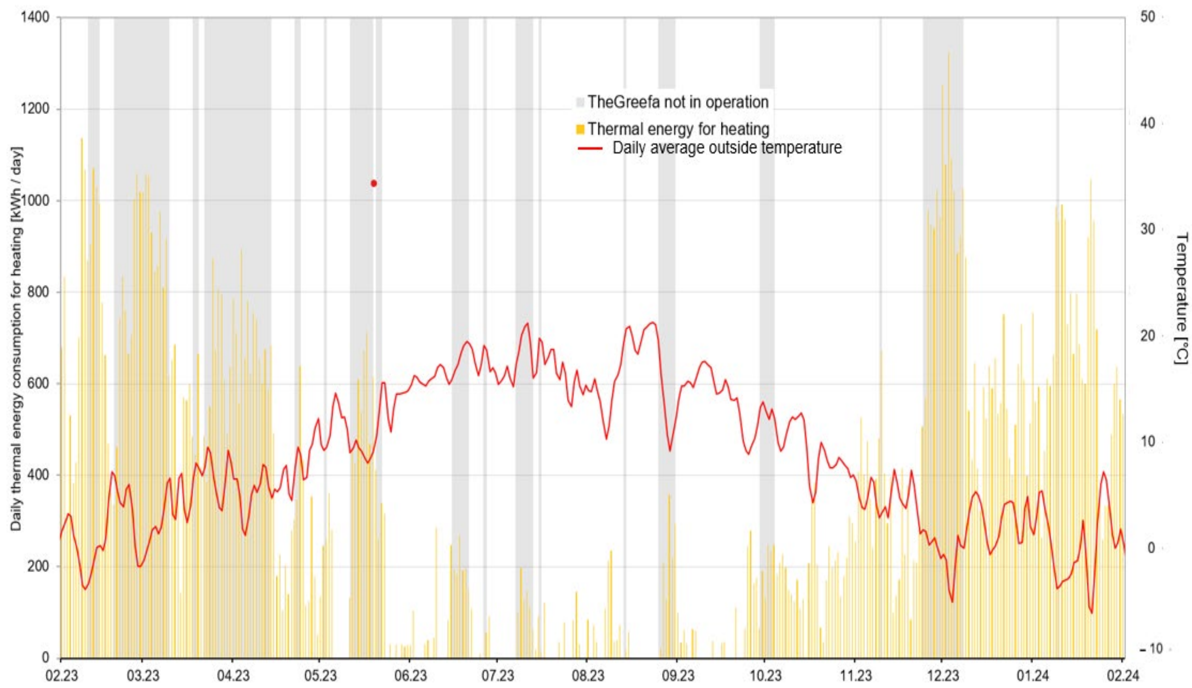

Figure 11: thermal energy consumption for heating in the greenhouse of TheGreefa during the demonstration period

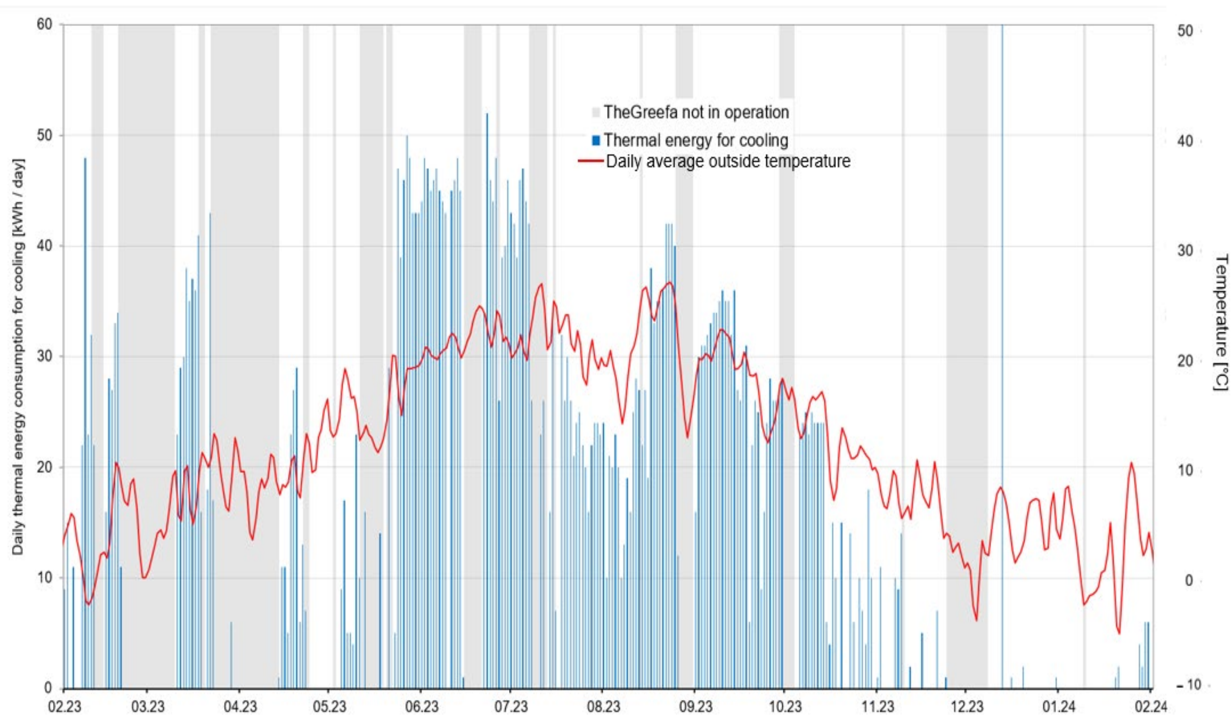

Figure 12: thermal energy consumption for cooling in the greenhouse of TheGreefa during the demonstration period

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It is clearly visible that heating follows a seasonal pattern, with a near zeroing during the summer period. Additionally, a peak in consumption can be observed during the phases when TheGreefa is not operational. This highlights how TheGreefa can help reduce thermal consumption for heating.

Cooling

The energy consumption for cooling over one year is reported in Figure 12. There are some peaks of consumption also in the cold period, February and March 2023. This was due to some test with the cooling before the installation and commissioning of the optimized evaporating cooling. Otherwise, the energy consumption follows a seasonal pattern.

The energy consumption for cooling is recorded by the heat meters Q20.4 for the absorber circuit. This is used also for the heating. As Figure 7, the absorber circuit can be operated in heating or cooling mode. In heating mode, the fluid of the circuit is heated in heat exchanger W20.2 by heat water of the heating system of Meyer Orchideen AG. In cooling mode, the fluid of the circuit is cooled down in the heat exchanger W20.3 by groundwater. The energy required in both operating modes is recorded by the Q20.4.

The energy required for cooling is in any case negligible in comparison to the energy for heating (Figure 11and Figure 12).

Electrical energy consumption

The electrical consumption considered in this and in the following sections relates to the pumps (Px.1) and the fans of the absorbers (VEx.1), the equipment installed directly to the absorbers. The consumption of other electrical components has not been considered as they are not specific to the TheGreefa system.

Electrical energy is not measured continuously. Instead of that, power measurements of the pumps and ventilators were carried out. Using the operating times, the electrical energy consumption data over time are calculated.

The electrical energy consumption is reported in Figure 13. The effective consumption of TheGreefa is reported in purple. This consumption has been integrated by the grey line to take in account the time when the entire system or single absorbers were not in operation. This is for a consistence with the thermal energy consumption; in case of thermal energy, the heating was supplied by TheGreefa shortage by another system; while in case of electrical energy. no electrical energy was consumed during the TheGreefa shortage. This gap are filled by the expected electrical energy consumption of TheGreefa.

As explained already in section 2.1, in July 2023 the operation of the system was optimised. Before this optimisation, the operation of all the absorbers were foreseen without interruption, that means the electrical consumption should have been constant at 320 kWh/day (all the pumps and ventilator in operation), see the grey line before July in Figure 13. A continuous operation of the absorbers was not necessary, the electrical consumption was too high. When suitable conditions for the plants are present, the absorbers can be turned off. The operation of an absorber depends on the table temperatures of the assigned tables (T0.x). If the table temperatures are in the range of comfortable temperature, the absorber remains off. If the designated temperature range is undercut or exceeded by one or more tables, the absorber turns on. This change in the operation strategy is very well

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recognisable in Figure 13, the consumption becomes significant lower since July. When the absorbers are in cooling mode, this mode is deactivated 3 hours before sunset.

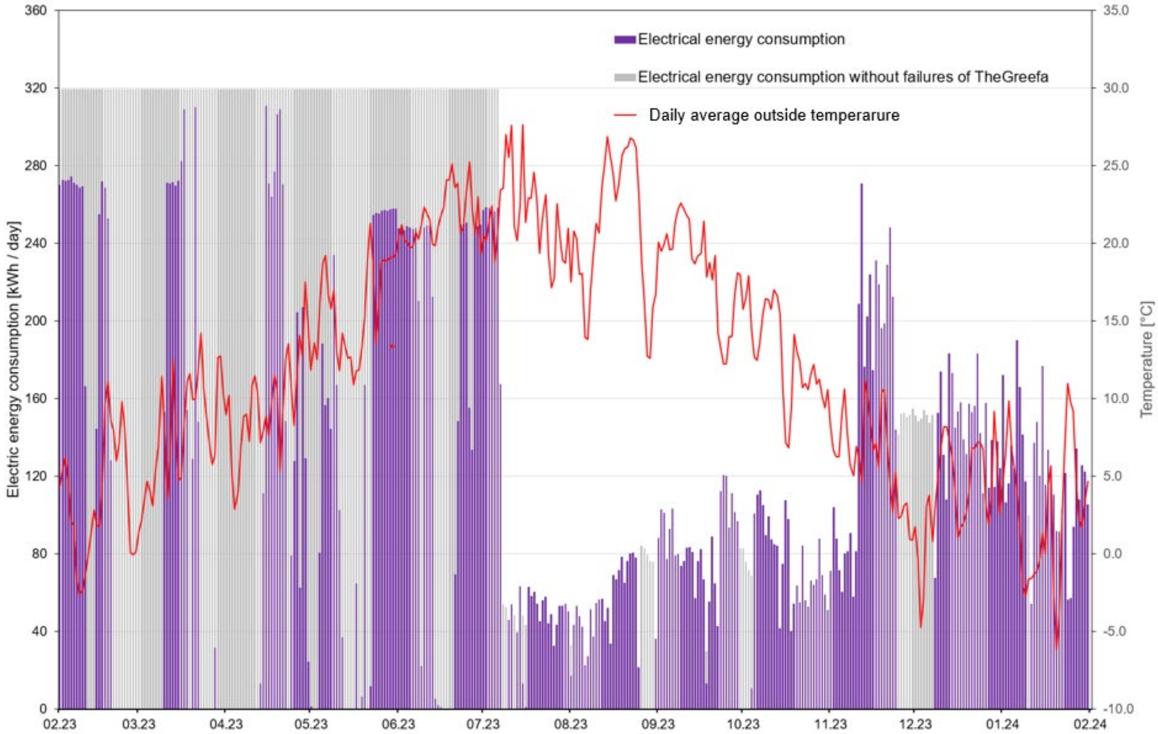

Figure 13: electrical energy consumption in the greenhouse of TheGreefa during the demonstration period

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Consumption of thermo-chemical fluid

The consumption of the thermochemical fluid is shown in Figure 14. It not directly measured in the demonstrator, but it is balanced by the amount of desorbed water from the solutionin the desorber. Referring to the P&ID sketch in Figure 5, the initial concentration ξ_{Des} (determinated by T10.1 and D10.1), and the filling volume V_{Des} (L10.3) before the desorption process are considered. Using the achieved final concentration ξ^{conc} of the TCF (set-up 32.5%) the desorbed water per desorbtion cycle can be calculated. The number of desorption cycles per unit time n_{des} is also recorded, so it is possible to determine the desorbed water per time unit M_{Wdes} (equation 1). To determinate the volume of concentrated TCF, the diluted TCF concentration ξ^{dil} and the density ρ are also used (Equation 2). ξ^{conc} and ξ^{dil} are set points of the demonstrator, 32.5% and 29.6% (please, refer to the operating manual D1.3).

(1) $$M_{Wdes} = V_{Des} \cdot \rho(T, \xi_{Des}) \cdot \left(1 - \frac{\xi_{Des}}{\xi_{Conc}}\right) \cdot n_{des}$$

(2) $$V_{conc.TFC} = \frac{m_{Wdes}}{\left(\frac{\xi^{dil}}{\xi^{conc}} - 1\right) \cdot \rho(T, \xi^{conc})}$$

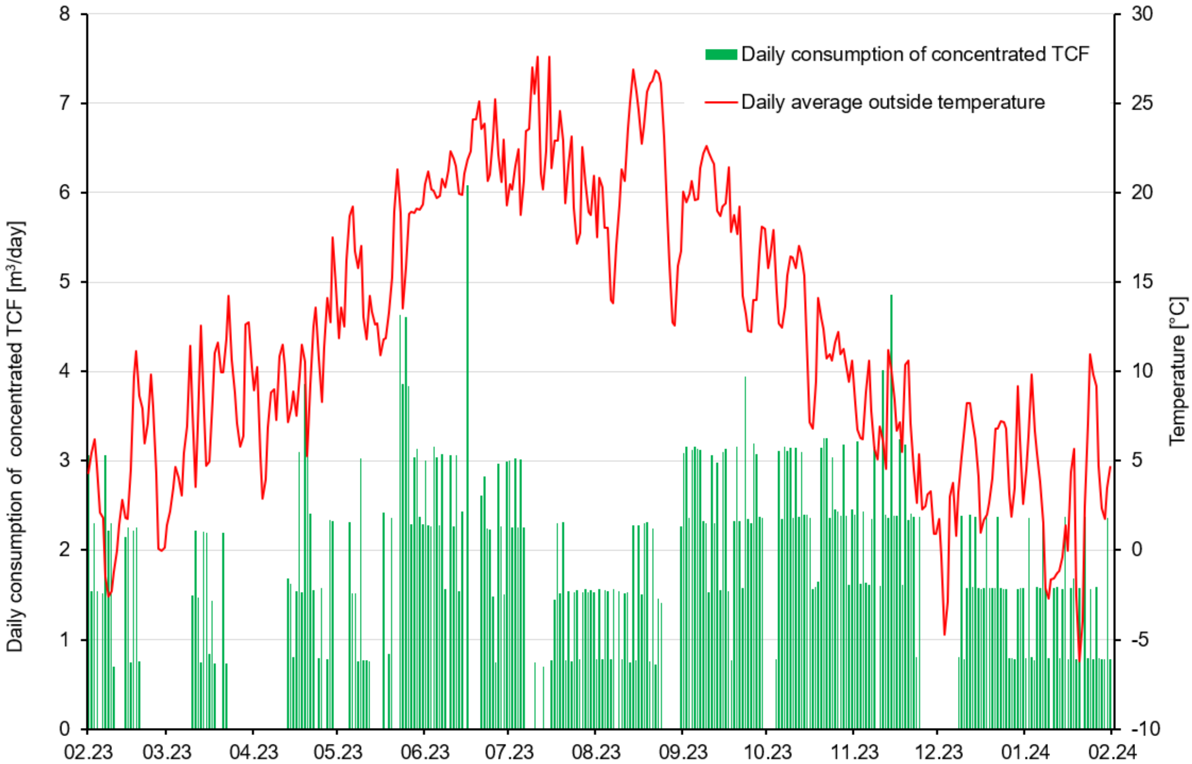

Figure 14: consumption of concentrated TCF (MgCl2, 32.5% concentration) in the greenhouse of TheGreefa during the demonstration period

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Consumption of water for evaporate cooling

The evaporate cooling was finalized in May 2023. Spray nozzles have been installed on the table (Figure 15). When the temperature exceeds the threshold level, evaporative cooling is activated. Water is supplied through solenoid valves that open at fixed time intervals. After several tests, a humidification duration of 200 milliseconds and an interval of 20 minutes was chosen for all tables. This selection of timing allows for dry pots and moist, non-dripping gravel, unlike what happens with too frequent or too long humidification.

Figure 15: spray nozzles for evaporating cooling

The consumption of the water for the evaporative cooling is shown in Figure 15.

The water is not directly recording by flowmeters. Water flowrate through the valves is known and the water consumption can be calculated by recording the number of activations of the solenoid valves.

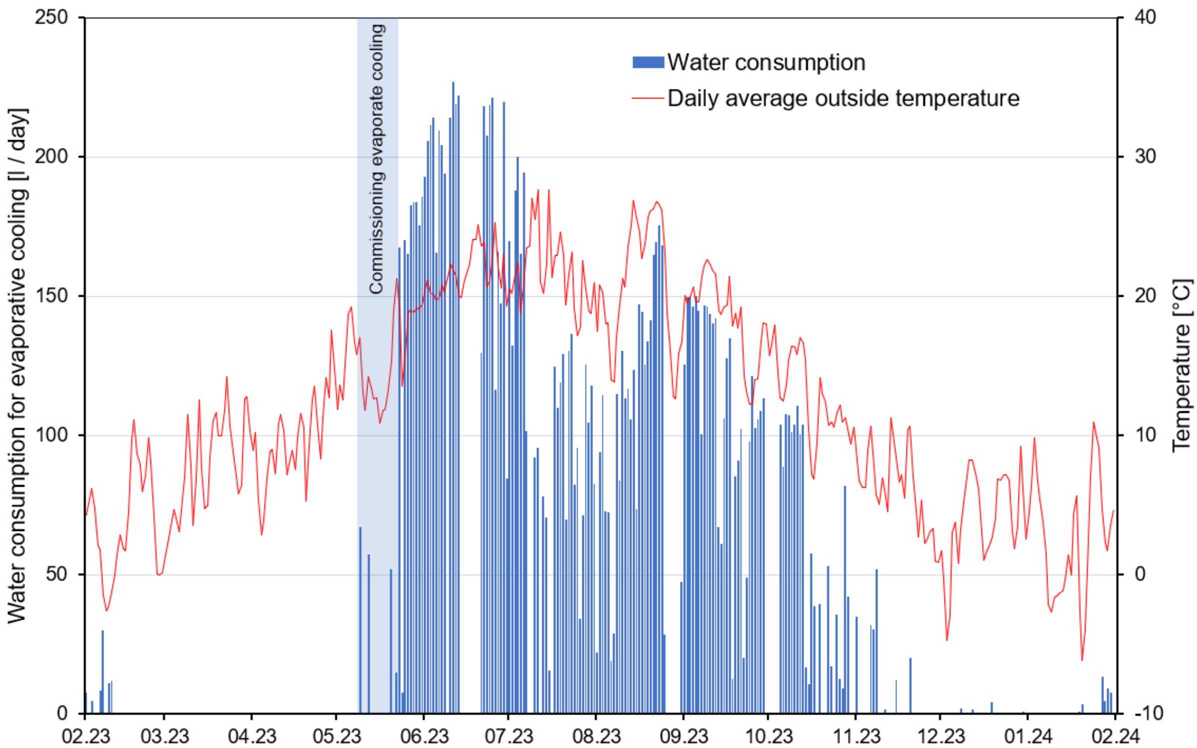

Figure 16: consumption of water for evaporite cooling in the greenhouse of TheGreefa during the demonstration period

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2.2.3 Consumptions for an optimised operation

The data reported in the previous section refer to measured data over one year in the demonstrator greenhouse. During this year, The Greefa was for 115 days out of service. Furthermore, the evaporative cooling system was finalised in May 2023, while an important optimisation in the operation concept was implemented in July 2023 (section 2.2.2, Electrical energy consumption).

The scope of this section is to present the consumption which will be occurred if the optimised demonstrator TheGreefa was running without interruption over that year.

Energy consumption

For the periods of operational interruptions, estimates are made based on the measured data using a regression function (Figure 17) depending on the outside temperature. For electrical consumption, the data after operational optimization in July 2023 is used to determine the regression function. The regression function is also used to estimate the consumption before optimization.

Expected values for thermal and electrical energy consumption are significantly lower than those measured in the demonstrator.

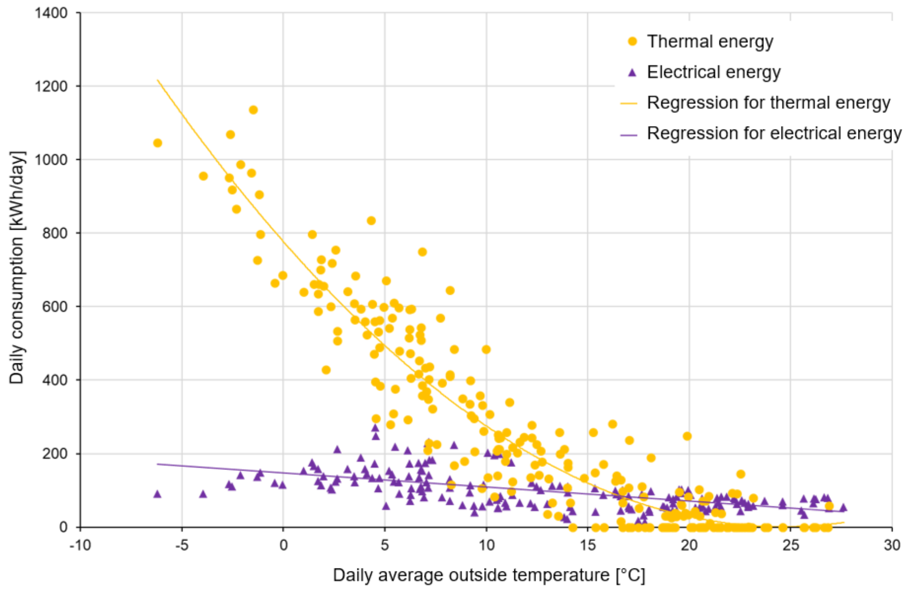

Figure 17: regression function for the estimation of the thermal and electrical energy consumption

The consumption peaks of the thermal energy consumption can be leveled out (Figure 18). These peaks were particularly present on days when TheGreefa was not in operation. The leveling is mainly due to the heat released during absorption, which therefore does not need to be supplied directly by the operator (see equation 8).

The expected electrical energy consumption has been reduced compared to that measured (Figure 19) thanks to a management strategy for switching individual absorbers on and off (section 2.2.2, Electrical energy consumption).

It is important to consider that the rotating components, such as the pumps and fans installed in TheGreefa, have not been optimized for their electrical performance. Additionally, the air ducts and

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heat exchangers were designed from a thermal perspective, leading to high pressure losses. Therefore, there is potential to reduce additional the electrical energy consumption.

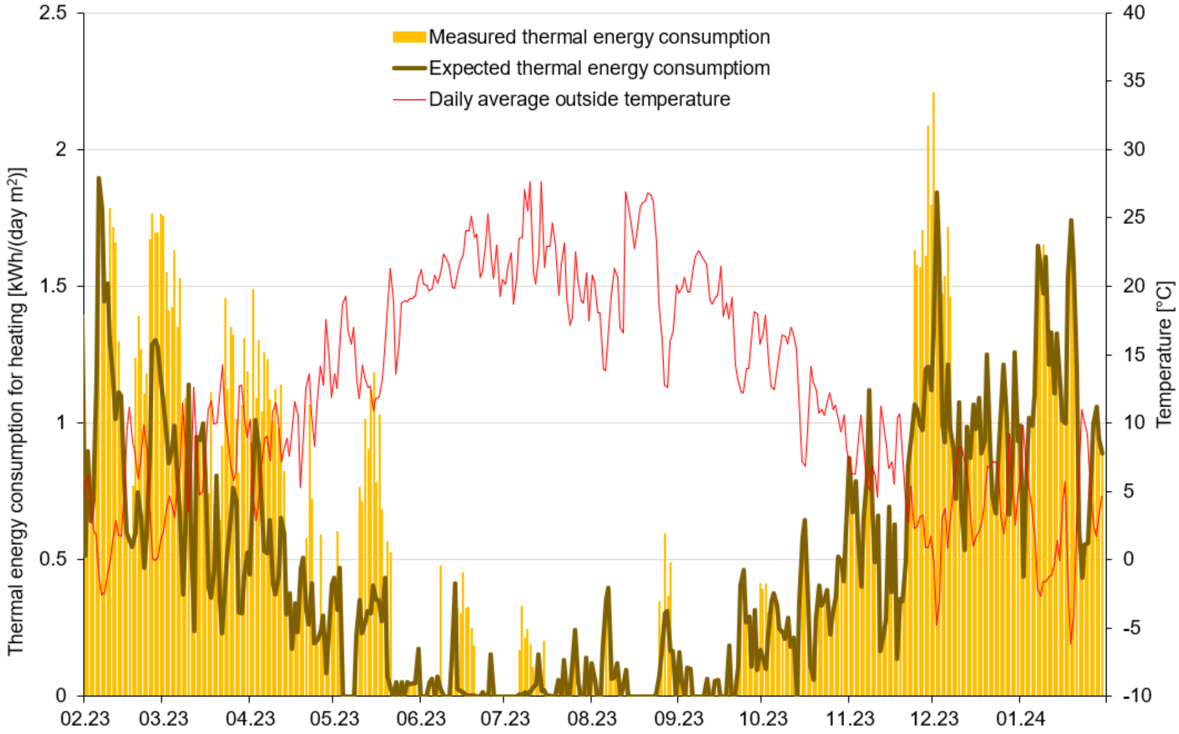

Figure 18: expected and measured thermal energy consumption for a square meter of TheGreefa

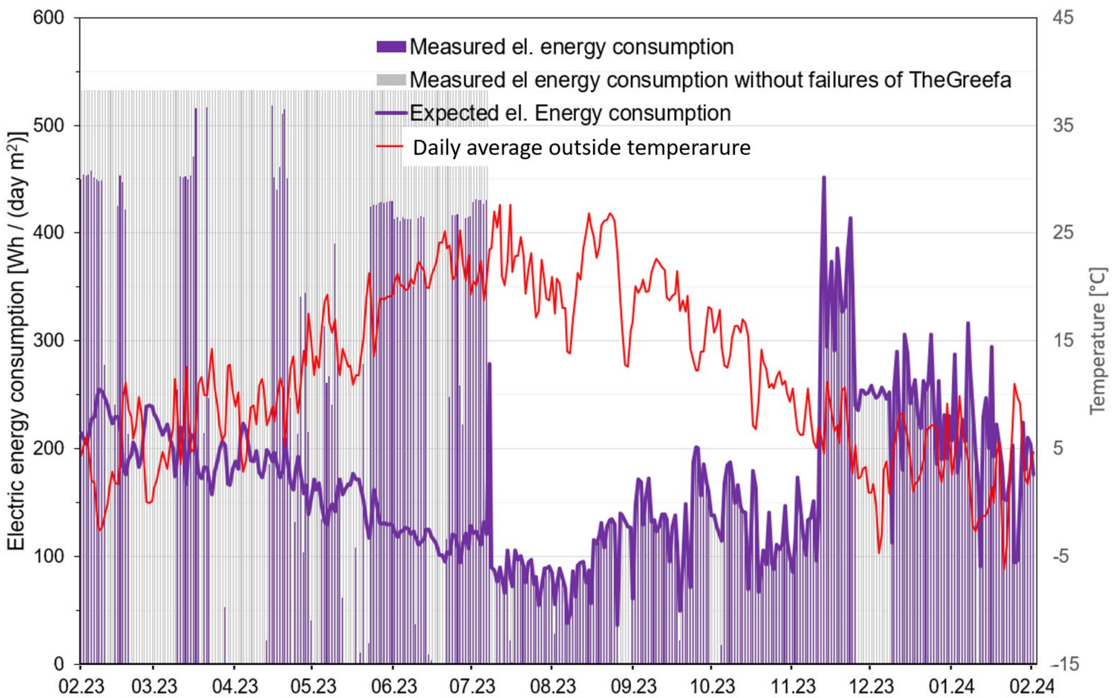

Figure 19: expected and measured electrical energy consumption for a square meter of TheGreefa

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Consumption of fluids

A regression function was also determined based on the measured data for water consumption in evaporative cooling (Figure 20) and for TCF concentrate consumption. This allowed for the estimation of water consumption even during the period when the evaporative cooling was not yet operational (before May 2023).

However, as shown in Figure 21, this estimation is overestimated. The water consumption values are overestimated. In fact, comparing the measured values from the last quarter of 2023 with the estimated values from the first two quarters of 2023, it is evident that the estimated values are higher despite having the same temperature.

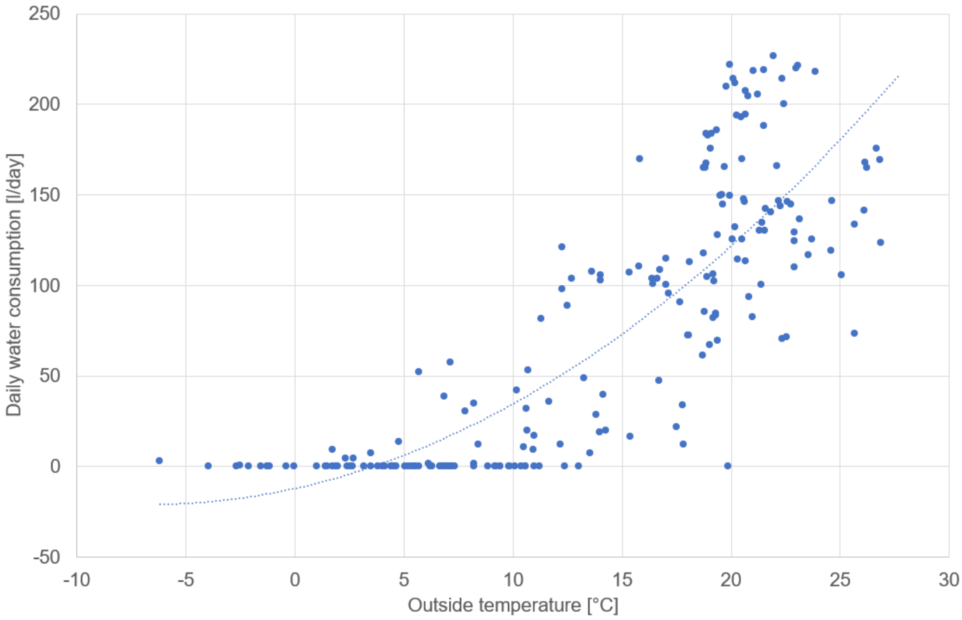

Figure 20: regression function for the estimation of the water consumption for evaporative cooling

With a similar regression function, the consumption of concentrated TCF has been determinate (Figure 22. This consumption closed the gap, where the TheGreefa was out of service.

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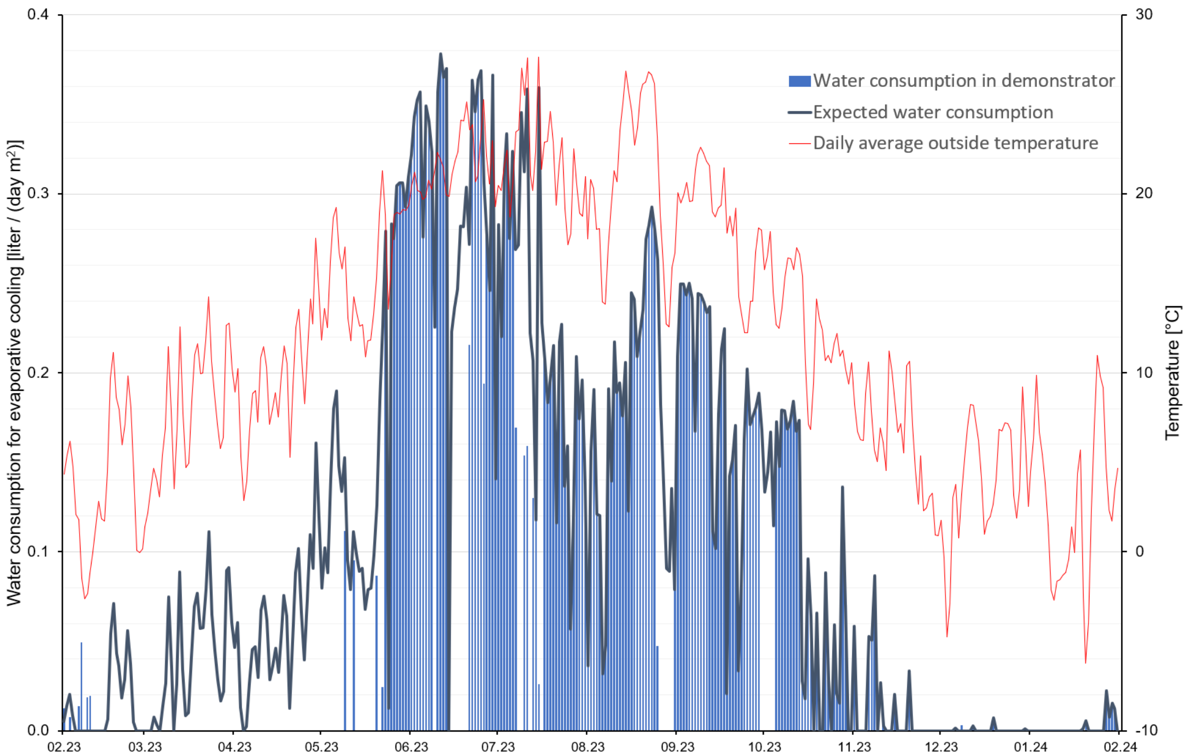

Figure 21: expected and measured water consumption for a square meter of TheGreefa

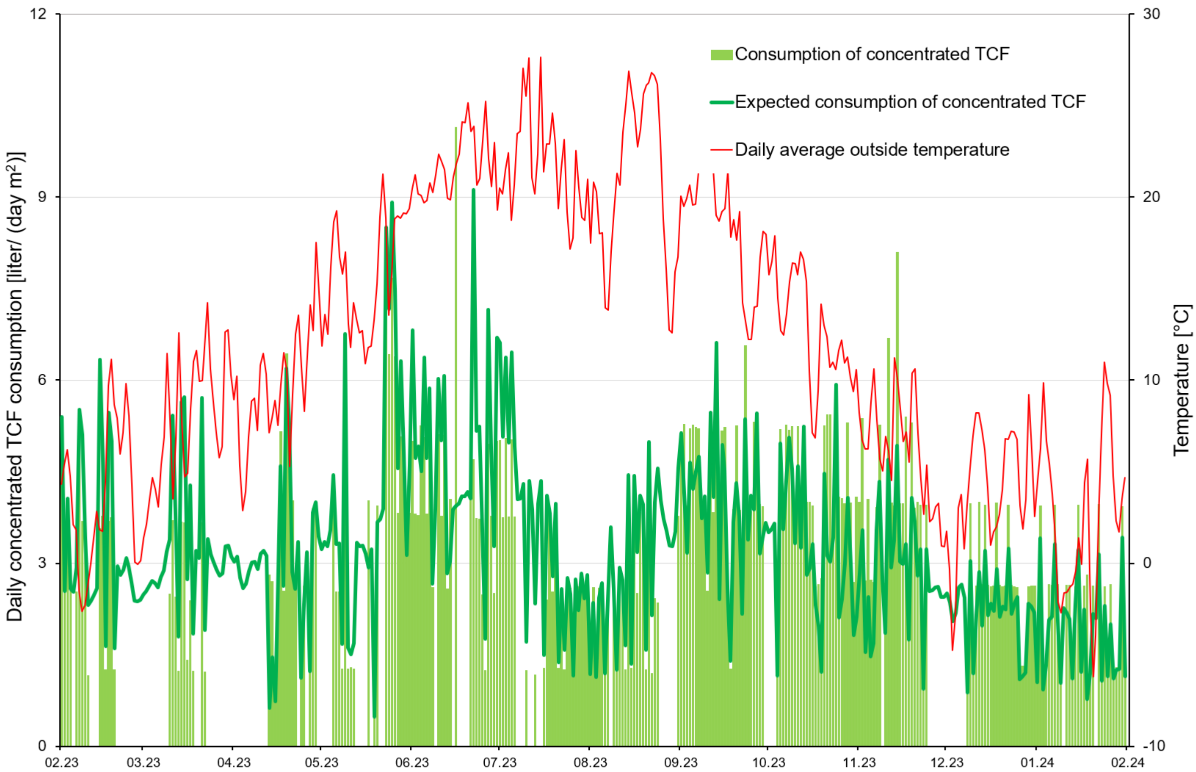

Figure 22: expected and measured consumption of concentrated TCF for a square meter of TheGreefa

This project has received funding from the European Union's Horizon 2020 research and innovation Programme under grant agreement 101000801.

2.3 Comparison of consumption in TheGreefa and in a standard greenhouse

After evaluating the expected consumption, it should be compared with a traditional installation for an equivalent greenhouse. The Meyer Orchideen AG greenhouse was in commercial operation throughout the project period, making it impossible to find a comparable greenhouse with the same characteristics. Therefore, based on the total consumption of the entire Meyer Orchideen AG facility, which includes 14 greenhouses, the consumption of greenhouse number 12, where the demonstrator was installed, was estimated without TheGreefa.

Operational data from the Meyer Orchideen AG greenhouse operation is read and documented monthly. These data include the heat quantities Q_{total} from the wood chip heating system, heat pump, and oil, as well as the amount of electricity W_{total} from the electrical grid. Different building structures and temperature levels in the greenhouses cannot be considered. The electrical consumption data for cooling in summer are related to the greenhouse 13 of Meyer Orchideen AG, which is cooled with refrigeration compressors.

Q_{GH12}	Thermal energy consumption of TheGreefa in greenhouse 12 (Figure 18)
Q_{total}	Total thermal energy consumption for the entire facility of Meyer Orchideen AG
W_{GH12}	Electrical energy consumption of TheGreefa in greenhouse 12 (Figure 19)
W_{GH13}	Electrical energy consumption in greenhouse 13
W_{total}	Total electrical energy consumption for the entire facility of Meyer Orchideen AG
A_{GH12}	Surface of the greenhouse 12 (TheGreefa)
A_{total}	Surface of the entire facility of Meyer Orchideen AG
q_{GH12}	Surface specific thermal energy consumption of the greenhouse 12 with TheGreefa
q_{conv}	Surface specific thermal energy consumption for an equivalent conventional greenhouse
$q_{abs\ GH12}$	Surface specific thermal energy released by the absorption process in TheGreefa
w_{GH12}	Surface specific electrical energy consumption of the greenhouse 12 with TheGreefa
w_{conv}	Surface specific electrical energy consumption for an equivalent conventional greenhouse
M_{Wdes}	Water absorbed by the absorption process in TheGreefa (see equation 1)
m_{Wdes}	Surface specific water absorbed by the absorption process in TheGreefa
h_{evap}	Evaporation enthalpy of water

From this data, comparison values for a conventional greenhouse are calculated.

<u>Electrical energy</u>

(3)
$$w_{GH12} = \frac{W_{GH12}}{A_{GH12}}$$

(4)
$$w_{conv} = \frac{W_{total} - W_{GH12} - W_{GH13}}{A_{total} - A_{GH12} - A_{GH13}} + \frac{W_{GH13}}{A_{GH13}}$$

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Thermal energy

(5) $$q_{GH12} = \frac{Q_{GH12}}{A_{GH12}}$$

(6) $$q_{conv} = \frac{Q_{total} - Q_{GH12}}{A_{total} - A_{GH12}}$$

Furthermore, it is calculated the specific heat released by the absorption.

(7) $$m_{Wdes} = \frac{M_{Wdes}}{A_{GH12}}$$

(8) $$q_{abs\ GH12} = m_{Wdes} \cdot h_{evap}$$

Based on data measured over more than a year and their interpolation (section 2.2.3), the energy savings achieved by Swiss greenhouses through TheGreefa technology have been estimated (Figure 23).

The 100% in the pie chart represents the thermal energy that would have been required in the convectional equivalent greenhouse. The red part indicates the energy saved by TheGreefa due to humidity control based on absorption instead of releasing warm and humid air to the outside. The blue part represents the thermal energy released during the absorption process (equation 8). This blue part is the energy needed to heat the greenhouse, but it does not have to be supplied by the greenhouse operator. It is the energy required for the regeneration of the TCF, for example low temperatures thermal energy, that would otherwise go unused. The characteristics of TheGreefa is that the availability of this energy does not need to coincide with the use, in time and in space. This energy can be stored for long periods without any energy loss in form of concentrated TCF, retaining potential rather than thermal energy. Finally, the grey segment is the thermal energy that must be supplied by the greenhouse operator.

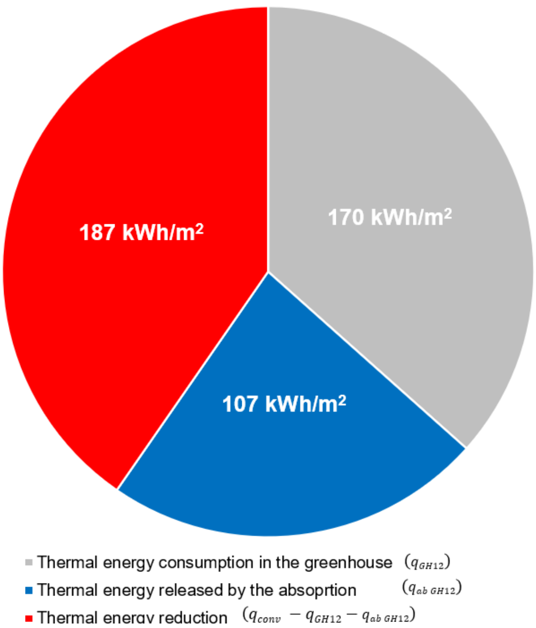

Figure 23: Pie charts for the specific expected thermal energy consumption per square meter of greenhouse area

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It is also important to understand when energy savings are primarily due to internal air recirculation (which prevents the need to open windows to regulate humidity) and when they are mainly due to the thermal energy released during the absorption process. This is illustrated in Figure 24. The grey bars indicate the actual thermal energy consumption, while the blue bars represent the energy released during absorption, both given as a percentage of the energy consumption of the conventional system. During the summer months, when overall thermal consumption is reduced, significant savings result from the energy released during absorption. In contrast, during the winter months, the savings are predominantly due to the internal recirculation effect.

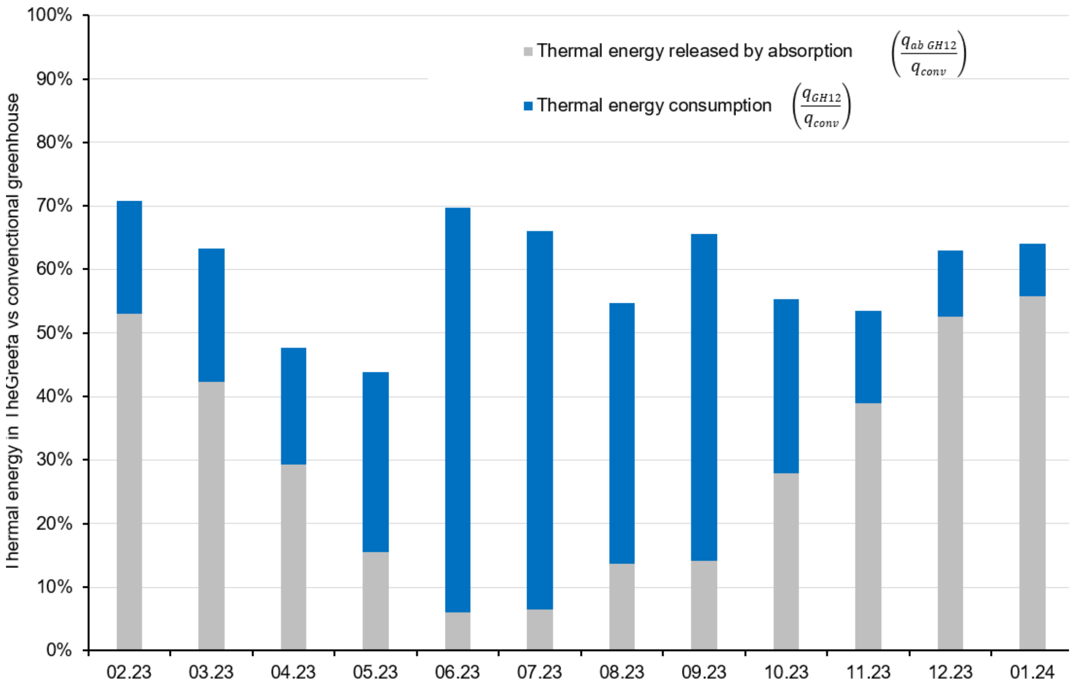

Figure 24: Excepted thermal energy consumption of TheGreefa relative to the conventional monthly consumption

For the electrical energy consumption, the situation is reversed. As shown in the Figure 25, electrical consumption increases with the installation of TheGreefa, by approximately 24%. It is noteworthy that electrical consumption is significantly lower compared to thermal consumption, with TheGreefa's electrical consumption being approximately one-third of its thermal consumption (62 kWh/m2 compared to 170 kWh/m2.

The rotating components, such as the pumps and fans installed in TheGreefa, were not optimised for their electrical performance. Additionally, the air ducts and heat exchangers were designed from a thermal perspective, leading to high pressure losses. Therefore, there is potential to reduce the additional consumption.

It is also important to understand the dependency of electrical energy consumption on seasonality. As shown in Figure 26, TheGreefa technology significantly reduces electrical consumption during the summer months, while consumption is much higher in the colder months. To understand this figure, it is important to note that at the Meyer Orchideen AG facility, cooling is provided by a compression machine with high electrical consumption, whereas heat is generated using a wood chip boiler and partly by a high COP heat pump (water/groundwater). Therefore, electrical energy consumption for

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Meyer Orchideen AG is very limited during the colder months, but high during the warner months. In regions with more prolonged hot periods, there could also be electrical energy savings.

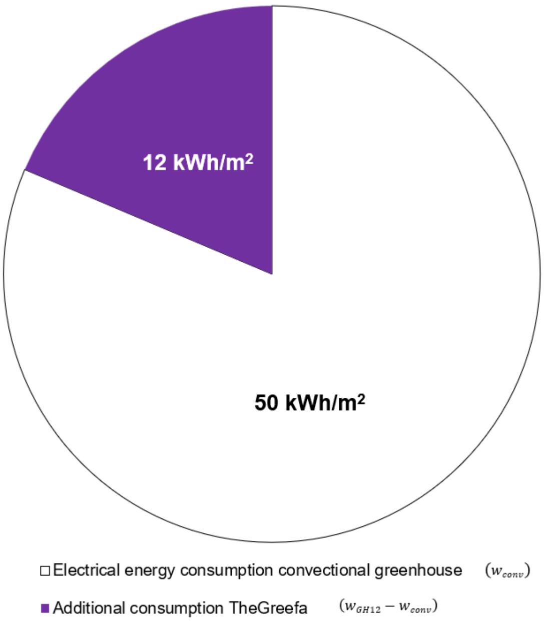

Figure 25: Pie charts for the expected specific electrical energy consumption per square meter of greenhouse area

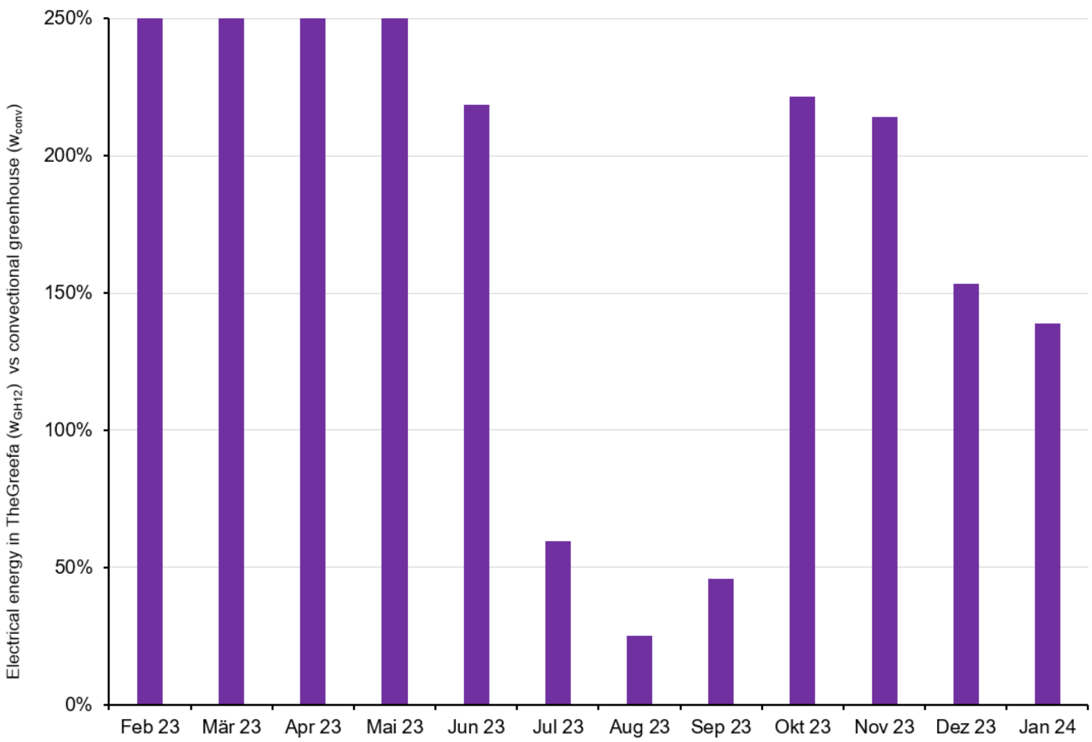

Figure 26: Excepted electrical energy consumption of TheGreefa relative to the conventional monthly consumption

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Utilities consumption

Expected specific consumptions of water for evaporating cooling and concentrated TCF are reported in Figure 27and Figure 28. The figures show that water consumption for evaporative cooling increases significantly during the hot months, from June to the end of October, as it is necessary to cool the greenhouse air. In contrast, the consumption of TCF remains fairly constant, as its use is primarily for dehumidification, which is necessary throughout the year due to plant transpiration.

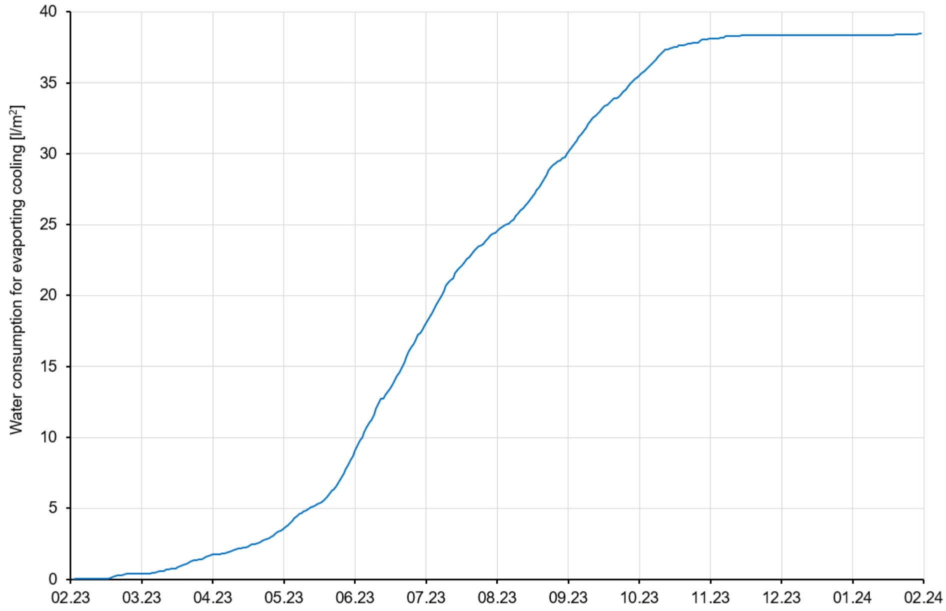

Figure 27: Consumption of water for evaporative cooling per square meter of greenhouse summed over the year

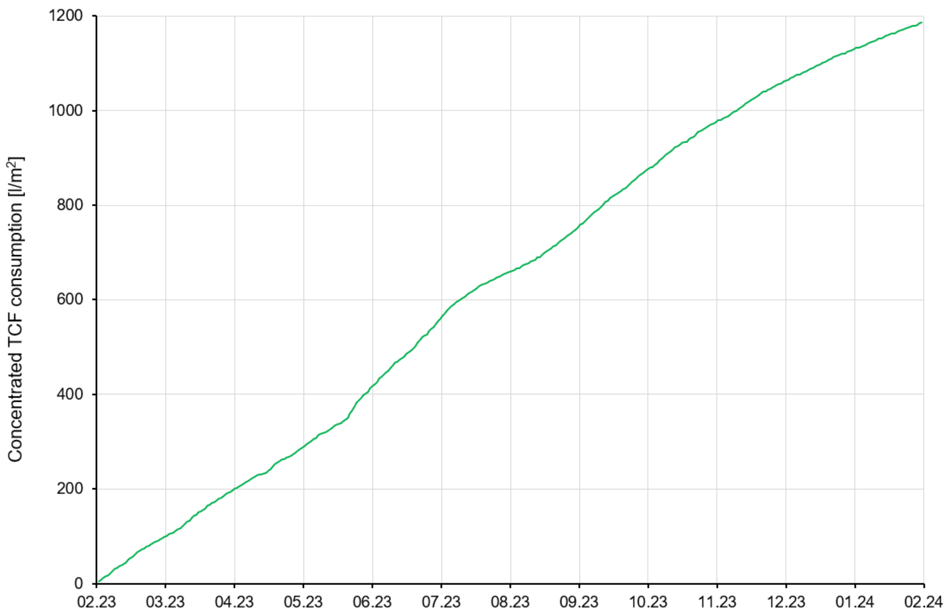

Figure 28: Consumption of concentrated TCF per square meter of greenhouse area summed over the year. . Specific values per square meter of greenhouse area

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2.4 Storage

A significant advantage of the technology proposed in TheGreefa is the ability to achieve seasonal thermal storage without losses. Thermal energy is converted into thermochemical potential and stored as concentrated TCF. This allows the use of low-temperature thermal energy for the regeneration process, with thermal energy being stored as concentrated TCF and utilized when and where it is needed. This approach fully decouples the production of concentrated TCF from its usage.
This aspect could not be tested in TheGreefa's demonstrator. Buffer storages, totaling 4 m^3, were used both because the CO_2-neutral thermal energy available from Meyer is continuous and due to cost and space constraints. Nonetheless, it was possible to simulate a system powered by solar thermal energy that would autonomously supply the demonstrator for the totally production of concentrated TCF (Figure 30).
The scope of the simulation was to dimension the thermal solar collector field and the storages. As inputs are used the expected flowrate of concentrated TCF required by the demonstrator (Figure 28) and the data from the weather station.

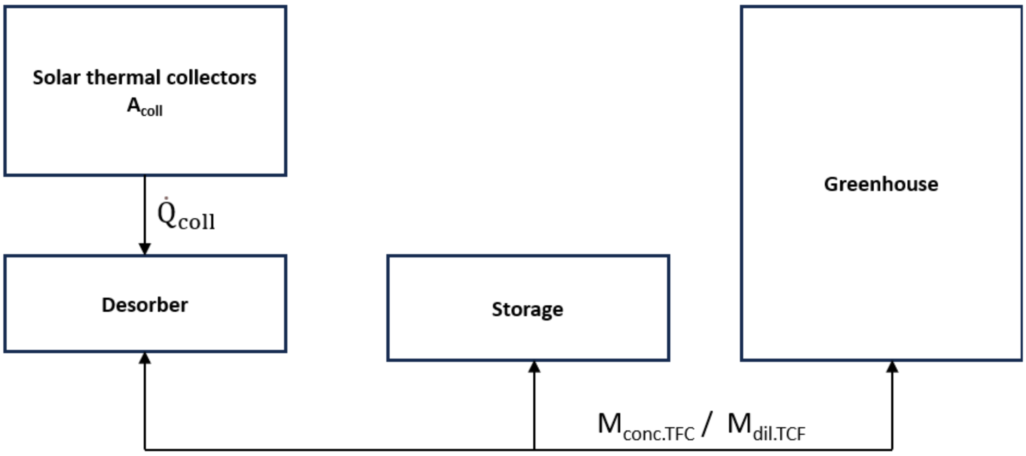

Figure 30: Block diagram of the system as a whole

The regeneration process is simulated as a closed system, as schematically illustrated in Figure 29.
The quantity of water that evaporates in the desorber equals the amount absorbed in the greenhouse. The water vapor from the desorber then condenses in the condenser, releasing the heat Q0. This energy, Q0, corresponds to the heat released during absorption $Q_{abs\ GH12}$ (equation 8 x M_{Wdes}). The thermal energy is stored in form of thermochemical potential in the concentrated TCF, $M_{conc.TCF}$.

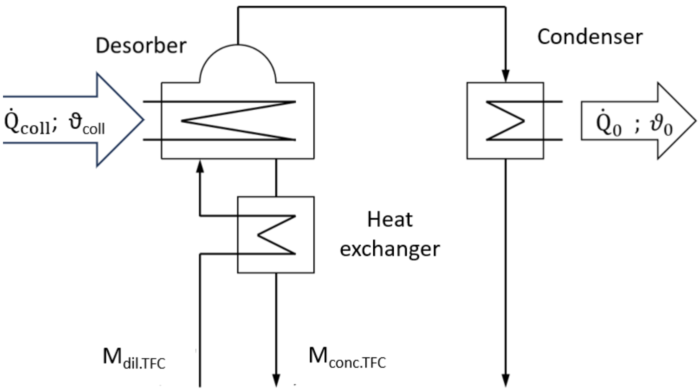

Figure 29: schematic of the simulated desorption system

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The following data are used for the simulation; they are recorded/expected data from the demonstrator, from weather station, collector data sheets:

- $\dot{Q}_0$ as explained before is the energy released in the conder and corresponds to $\dot{Q}_{abs\ GH12}$
- $M_{conc.TFC}$ or $M_{dil.TCF}$ are the amount of concentrated and diluted TCF (see)
- ϑ_0 is the ambient temperature
- E is the solar radiation
- $\eta_0, \alpha_1, \alpha_2$ are characteristic of the thermal solar collector
- $\xi_{conc.TCF}$ is the concentration of the concentrated TCF
- $\xi_{conc.TCF}$ is the concentration of the diluted TCF
- $\vartheta_{dil.TCF}$ is the temperature of the diluted TCF

Substance properties are:

- p_{H2O} is the vapor pressure of water at ambient temperature
- $H_{conc.TCF}$ and $H_{dil.TCF}$ are the enthalpies of the concentrated and diluted TCF

The output of the simulation are

- $\dot{Q}_{coll}$ is the thermal energy from the solar collectors and the driving energy of the regeneration process
- ϑ_{coll} is the collector temperature
- A_{coll} is the surface of the thermal solar collectors

Variables for the optimization are

- ΔT temperature difference between TCF and temperature of the heat input in the desorber and in the heat exchanger
- Inclination and direction of solar collectors

The heat output Q_o occurs at ambient temperature, while the heat input Q_{coll} occurs at collector temperature ϑ_{coll} .

The temperature at collector ϑ_{coll} corresponds to the boiling temperature of the concentrated solution $\vartheta_{conc.TCF}$, plus ΔT at the operating pressure, which is equal to the (equation 9).

(9) $$\vartheta_{coll} = \vartheta_{conc.TCF}\left(p_{H2O}(\vartheta_0 + \Delta T), \xi_{conc.TCF}\ \right) + \Delta T$$

The temperature of the concentrated TCF is determined by the heat balance around the heat exchanger.

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The heat driving the process $\dot{Q}_{coll}$ results from the heat balance of the desorption system (equation 10).

(10) $$\dot{Q}_{coll} = \dot{Q}_0 + H_{conc.TCF} - H_{dil.TCF}$$

The driving energy is a function of the data of solar collector, solar radiation E, surface of the solar collectors, collector temperature and ambient temperature. Through the equation 11, it is possible to calculate the area of the solar collectors

(11) $$Q_{coll} = \int_{\tau_1}^{\tau_2} \left(\eta_0 \cdot E \cdot A_{coll} - (\alpha_1 \cdot A_{coll} \cdot (\vartheta_K - \vartheta_o) + \alpha_2 \cdot A_{coll} \cdot (\vartheta_K - \vartheta_o)^2)\right) \cdot d\tau$$

The exchange of the TCF to and from the greenhouse is described through a storage simulation over a one-year period (τ_2-τ_1 = 1 year). No losses occur. The storages can be filled with concentrated or diluted solution as needed. The storage allows dilution and concentration to be temporally decoupled.

For the simulation was assumed a minimum driving force of ΔT=5K. Heat losses in the desorber, condenser and heat exchanger are not considered.

The solar collectors are facing the south, have an inclination of 45°C and are the model installed at the ZHAW facility: $\eta_0 = 0.754, \alpha_1 = 3.66 \; and \; \alpha_2 = 0.0078$.

The simulation results in a solar thermal system with flat-plate collectors covering an area of 100m², and the required storage volume is 100m³. These values refer to the demonstrator greenhouse covering a surface of 600m².

Based on measured data of concentrated TCF used in the demonstrator (blue line), the production of concentrated TCF (green line) was simulated. As heat source is used warm water generated by thermal solar panels located near the greenhouse.

Figure 31 shows the annual cumulative water absorbed by the absorber and the simulated water desorbed by the desorber, proportional to the TCF production. It is interesting to note that the TCF regeneration occurs year-round with a slight decrease during colder months due to shorter days and increased cloud cover. For the TCF regeneration it is important to maintain a temperature difference between solar collector and TCF rather to reach a high absolute temperature at the usage side (TCF) as in conventional solar collectors. As result, the thermal losses from the solar collector of TheGreefa remain nearly constant throughout the year. As a result, there are no significant fluctuations in yield over the year. The storage compensates for the fluctuations in radiation power.

Based on the quantity and usage pattern of TCF used and regenerated, the minimum required size for TCF storage has been determined (Figure 31). Only one storage unit is needed, as the different densities of concentrated and diluted TCF prevent them from mixing.

During the cold season, TCF usage is high while regeneration is slightly lower. By the end of this season (March), the storage is fully occupied by diluted TCF. Conversely, at the end of the warm season, due to opposite conditions, the storage is entirely filled with concentrated TCF.

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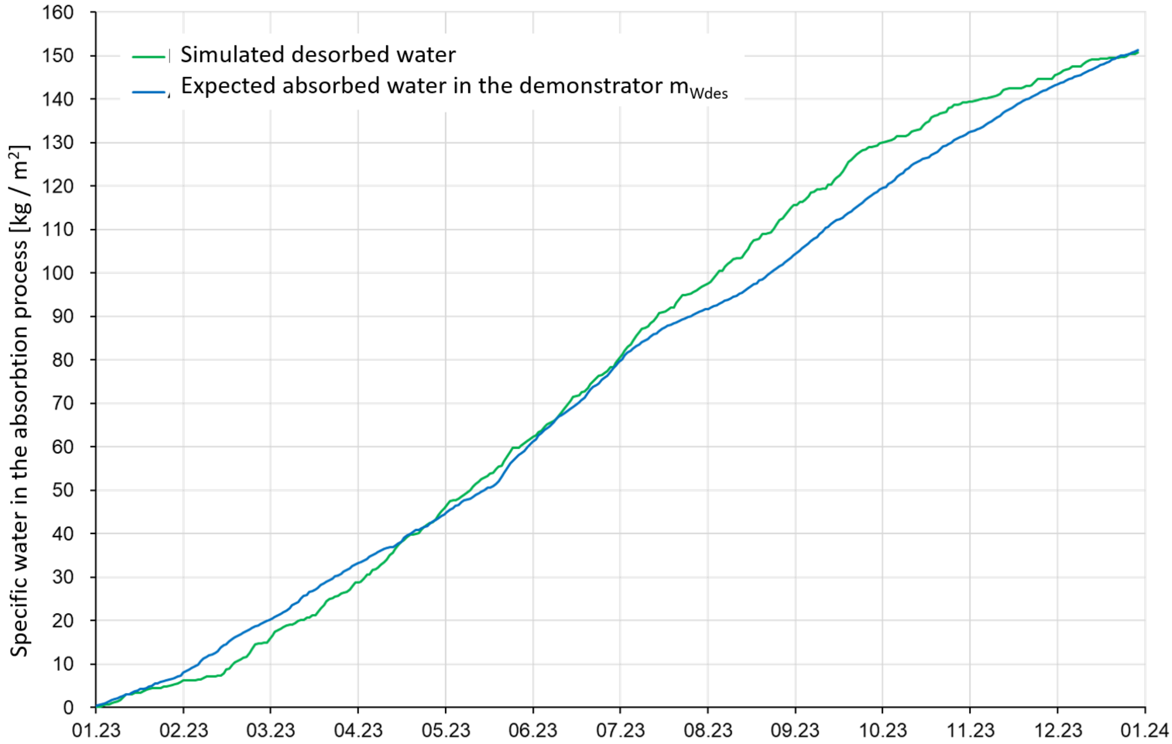

Figure 31: Cumulative absorbed water expected in TheGreefa and simulated desorbed water. . Specific values per square meter of greenhouse area

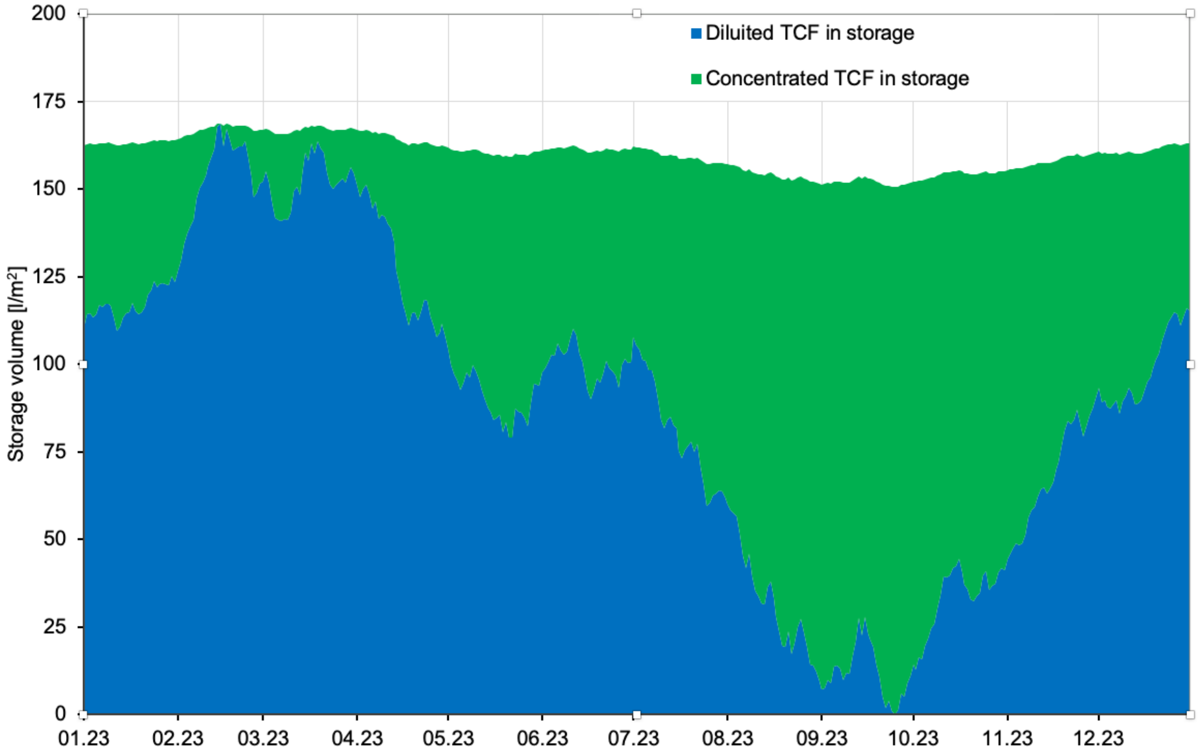

Figure 32: Filling profile of the TCF storage, highlighting the levels of concentrated and diluted TCF. Specific values per square meter of greenhouse area

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An important consideration for storage, especially for long-term purposes, is the quality of the stored liquid. TheGreefa's storage tanks containing TCF have been located outside the greenhouse since 2017. These are basic plastic IBC tanks (Figure 4). There is a slight risk of TCF concentration degradation if it interacts with dry air, although this issue has either never occurred or has been imperceptible if it did. The volume of air within the tank and the surface area where air contacts the TCF are minimal, allowing for rapid establishment of phase equilibrium between the air and TCF inside the tank.

Issues with the TCF arose at the beginning of 2023 when the demonstration period was set to start. Operational failures occurred, which were traced back to crystal formation in the membrane pumps. Besides deposits in the pumps, Carnallite had settled in the tanks of the concentrated solution (Figure 32). No deposits were found in other parts of the system. An XRD (X-ray diffraction) analysis of the discovered crystals (Figure 33) identified them as Carnallite ($KMgCl_3 \cdot 6H_2O$). Additionally, hexahydrate and bihydrate of magnesium chloride were detected as minor components.

Figure 33: Membrane pump with crystal formation (left). Crystal formation in the concentrated TCF tank (right).

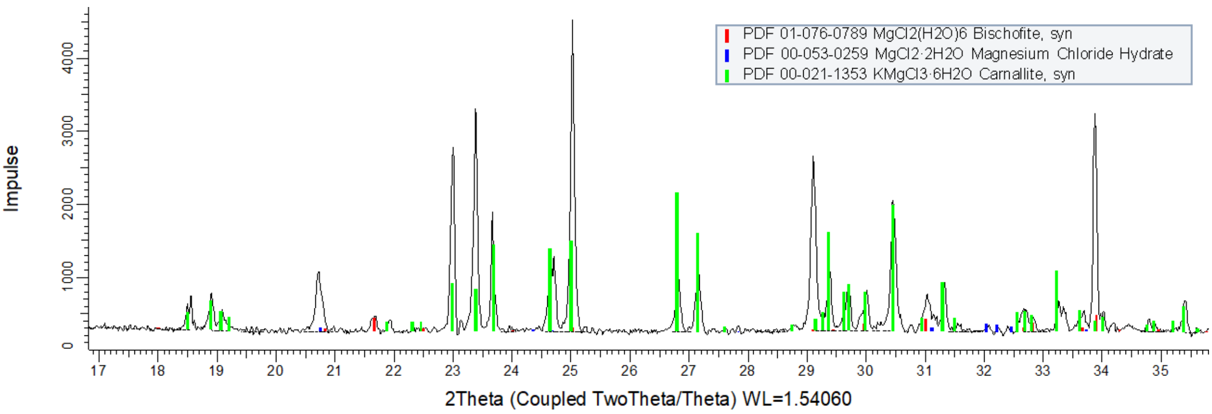

Figure 34: X-ray diffraction of the examined crystals from the membrane pump

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Whether potassium was introduced into the process is a key question regarding this issue. To investigate this, an ICP-OES (inductively coupled plasma optical emission spectrometry) analysis was conducted. The potassium content was determined in three solutions based on the measured ions.

Sample 1: TCF from demonstrator used till December 2022	3.18% Potassium
Sample 2: TCF from demonstrator used till March 2023	2.41% Potassium
Sample 3: unused TCF of Febraury 2023	2.74% Potassium

A comparison with unused solution from another batch from the same supplier showed a similarly high potassium content. Over time, the potassium content in the test system solution decreased due to deposits in the concentrated solution tank. From these findings, it can be concluded that the potassium was not introduced during operation but was already present in the solution when it was procured.

2.5 Conclusions

The functionality of the TheGreefa system installed in the greenhouse was tested for more than a year. Data from periods when the system was out of service (both planned and unplanned) were interpolated. The temperature and humidity of the air produced in the individual absorbers can be controlled very precisely by adjusting the temperature and concentration of the TCF. Therefore, the functionality of the absorber was tested and met expectations.

Unfortunately, different results were obtained with the table system. The goal was to create a microclimate on each table. While the air temperature at the absorber outlet can be maintained consistently regardless of fluctuations in greenhouse temperature, the temperature above the tables follows these fluctuations (refer to deliverable D1.2). This was associated to thermal losses due too long transport distance of the air (air duct below the tables, from the absorber outlet and the crops). A possible solution could be redesigning the absorber configuration, installing smaller absorbers directly below the tables and eliminating the need for air ducts. This solution was successfully tested for drying application in a parallel project by the ZHAW team, funded by the Swiss Federal Office of Energy (SONITRO, sorptive dryer, SI/502013-01). However, the new configuration was not introduced in TheGreefa due to time and budget constraints.

Despite this issue, during the cooling mode, the temperature above the tables can be maintained at a constant level because the spray nozzles for evaporative cooling are located directly on the tables. However, during the heating period, the temperature on the tables still follows the fluctuations of the greenhouse temperature. Nevertheless, the temperature remained within the acceptable range, and there was no real need to change the configuration.

The evaluation of a one-year operating period demonstrated an energy savings of more than 50%. Considering the thermal energy, the saving is more than 60%, while the consumption of electrical energy is increased more than 24%.

Additionally, heat is necessary for regenerating the TCF (Thermal Control Fluid), but this should not significantly impact costs since waste heat or otherwise unused heat can be utilized. Regeneration of the TCF does not necessarily have to occur on-site; alternatively, it could be supplied, for instance, by

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a thermochemical network (H2020 project H-Disnet, GA 695780); 1200 liters TCF per square meter of greenhouse surface is the yearly consumption.
The water consumption for the evaporating cooling will not impact the total economy of water of a greenhouse being around 40 liters per square meter of greenhouse surface (continual climate).

The data obtained for the demonstrator in Switzerland are summarized in Table 1. The comparison is for TheGreefa and for a conventional greenhouse equivalent to TheGreefa. The storage and the solar panel field have been sized to make the plant self-sufficient for TCF production. Please note the specificity of the greenhouse for the demonstrator, where orchids are cultivated and the plants are placed on tables, resulting in a single height level.

Table 1: data for TheGreefa greenhouse and for an conventional greenhouse. Storage and solar collectors are for a self-sufficient greenhouse for the TCF production

		TheGreefa greenhouse	Convectional greenhouse
Thermal energy	kWh/year	170	464
Electrical energy	kWh/year	62	50
Total energy consumption	**kWh/year**	**232**	**514**
Energy for regeneration (low temp. heat)	kWh/year	107	
Total energy consumption incl. regeneration	**kWh/year**	**339**	**514**
Water consumption for evaporative cooling	m^3/year	24	
TCF consumption	m^3/year	700	
TCF storage	m^3	105	
Solar thermal collector surface	m^2	100	

This absorption technology has shown considerable potential. The absorber manages both air temperature and humidity. Technically, the challenge lies in constructing a complete system with minimal or ideally no losses in air transport.

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3 Facility at INRGREF for Mediterranea regions

As the studied system is installed at the test facility of the INRGREF, the meteorological data used in the current study are specific to the Tunis region. The capital of Tunisia situated at 36.84° latitude and 10.18° longitude. The greenhouse is located at an elevation of 43 meters above sea level. Tunis has a Mediterranean, hot summer climate as classified by the Koppen-Geiger system [40].

In 2022, the mean temperature has reached 22.8°C. In winter, the mean value of temperature was about 15°C, whereas the mean minimum value dropped to 10°C. In summer, the mean temperature was about 32°C, contrarily to the maximum mean values reached 37°C. The mean VPD values ranged from 1530 Pa recorded in summer to 120 Pa in early spring. Due to this climatic variability, Tunisia is considered one of the most exposed countries to climate change in the Mediterranean area. So far, associated risks mentioned in the literature are temperature increase, precipitation decrease, sea level rise, and more frequent extreme weather phenomena like floods and droughts. During the last 30 years, the temperature has increased by an average of 0.4°C per decade and the average annual precipitation has decreased by about 3%. Thus, greenhouses are needed for an extended harvesting season under the Tunisian climate.

3.1 Measurement System

The assessment of the performance of the air conditioning system installed in Cherfech greenhouse requires a series of measurements.

The experimental monitoring involves the measurement of:

- The air temperature and humidity at different positions inside the greenhouse,
- The CO_2 concentration of the air inside the greenhouse.
- The air temperature and humidity at the inlet and the outlet of the absorbers' devices,
- The desiccant temperature at different positions of the hydraulic system,
- The soil temperature at three different positions,
- The flow rate of the desiccant solution at the inlet of the absorbers' devices,
- The level of the desiccant solution inside the storage tank.

To this aim, a set of sensors was installed inside the greenhouse, as well as in the air pipes and the desiccant pipes, as detailed below:

- 4 Humidity and temperature sensors for condensing environment (NSENS-HT-EIH)
- 8 Humidity and temperature sensors (NSENS-HT-CSP)
- 16 Temperature sensors (PT100)
- 2 Electromagnetic flowmeters (FM100)
- 1 Radar level transmitter (SITRANS LR100)

The positions and characteristics of the sensors are detailed in Table 2and Table 3 as well as on Figure 35.

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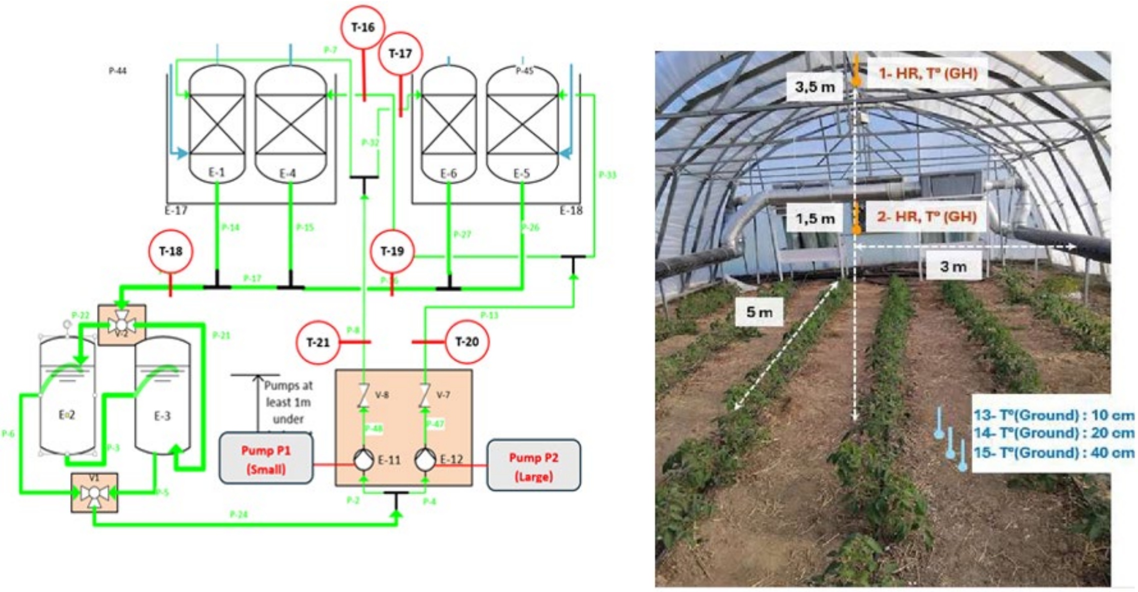

Figure 35: Positions of the air temperature sensors in the greenhouse (right) and positions of the desiccant temperature sensors within the hydraulic system and

Table 2: Position of the sensors installed in Cherfech Greenhouse

Qtty	N°	Measuring	Type *	Position
12	**Humidity and Temperature Sensors**			
4	**1**	HR, T of Air	A	Inside the GH – High Level (3,5 m)
	2	HR, T of Air	A	Inside the GH – Plantings Level (1,5 m))
	3	HR, T of Air	A	At the inlet of Absorbers
	4	HR, T of Air	A	Attached to Arch 4 (Right, Height =2,3)
8	**5**	HR, T of Air	B	Air duct at the outlet 1 of Absorber 1
	6	HR, T of Air	B	Air duct at the outlet 2 of Absorber 1
	7	HR, T of Air	B	Air duct at the outlet 1 of Absorber 2
	8	HR, T of Air	B	Air duct at the outlet 2 of Absorber 2
	9	HR, T of Air	B	Attached to Arch 1 (Right, Height = 2,3)
	10	HR, T of Air	B	Attached to Arch 2 (Left, Height = 2,3)
	11	HR, T of Air	B	Attached to Arch 6 (Left, Height = 2,3)
	12	HR, T of Air	B	Attached to Arch 5 (Close to the cover)
16	**Temperature Sensors**			
3	**13**	T of soil	C	In the ground (in the middle of the GH) : Depth = 10 cm
	14	T of soil	C	In the ground (in the middle of the GH) : Depth = 20 cm
	15	T of soil	C	In the ground (in the middle of the GH) : Depth = 30 cm
6	**16**	T of Desiccant	C	Desiccant pipe at inlet of E4 - Absorber 1

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	17	T of Desiccant	C	Desiccant pipe at inlet of E6 - Absorber 2
	18	T of Desiccant	C	Desiccant pipe at the outlet of Absorber 1
	19	T of Desiccant	C	Desiccant pipe at the outlet of Absorber 2
	20	T of Desiccant	C	Desiccant pipe at the outlet of Pump 1
	21	T of Desiccant	C	Desiccant pipe at the outlet of Pump 2
7	22	T of air	C	Temperature Inside the GH (Control Box) 1,5m
	23	T of air	C	Inside the lateral air supply line (Right)
	24	T of air	C	Inside the lateral air supply line (Left)
	25	T of air	C	Attached to Arch 3 (Right, Height <= 2,3)
	26	T of air	C	Attached to Arch 7 (Left, Height <= 2,3)
	27	T of air	C	Inside the GH – Height (1 m)
	28	T of air	C	Ambient Air (Outside the GH)
	Flowmeter			
2	29	Flowrate	D	Desiccant pipe at the inlet of Absorber 1,2 (Pump1)
	30	Flowrate	D	Desiccant pipe at the inlet of Absorber 1,2 (Pump2)

Table 3: Characteristics of the sensors installed in Cherfech Greenhouse

*	Qtty	Type	Description	Symbol
A	4	NSENS-HT-EIH	Humidity and temperature Sensor (for condensing environment)	
B	8	NSENS-HT-CSP	Humidity and temperature sensor	
C	16	PT 100	Temperature sensors	
D	2	FM100	Electromagnetic Flowmeter	

A smart acquisition system was installed to record the values measured by these sensors every 15 minutes. This system automates data acquisition processes, provides remote access to collected data, and enables remote monitoring of sensors.

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The Control System

The air conditioning system of the greenhouse is controlled by a control box (Figure 36) that compares the temperature inside the center of the greenhouse (T_{GH}), measured by sensor N°22 of the monitoring system to the temperature of the desiccant stored in the storage tank.

Two temperature sensors were immersed in the liquid solution: one at the bottom (T_4) and one just below the top surface of the liquid (T_2). The placement of the sensors is indicated in Figure 37. In the first step, based on the comparison between the greenhouse temperature and the desiccant temperatures, the system is switched to either day or night mode. Day mode is specified for greenhouse cooling and dehumidification, while night mode is aimed at cooling the storage back to the original value from the cycle a day earlier. Day and night mode is switched by two actuators, being valve 1 and 2 (V1, V2). The blueprint indicating the electric connections and dependencies between control box, sensors and actuators is indicated on Figure 38.

In a second step, based on the comparison between the greenhouse temperature and predefined setpoint temperatures, the system operates in one of three stages (Stage 1, Stage 2, or Stage 3):
In stage 1, the small pump is activated and delivers the desiccant solution to the absorbers' small compartments including a smaller ventilator. In stage 2, the larger pump is activated and supplies the solution to the larger compartments with larger ventilator. In stage 3, all pumps and ventilators operate simultaneously.

For example, in initial experiments that started at the end of April 2024:

- stage 1 was activated when T_{GH} reached 35 °C,
- stage 2 was activated when T_{GH} reached 38 °C,
- stage 3 was activated when T_{GH} exceeded 41 °C.

Besides, there is an emergency ventilation device, providing ambient air and opening the closed greenhouse. It uses an independent control (thermostat). The ventilation setpoint is above the stage 3 setpoint. A similar temperature value is forcing the cooling system off.

Figure 36: The Control Box used for system Monitoring (Siemens LOGO!)

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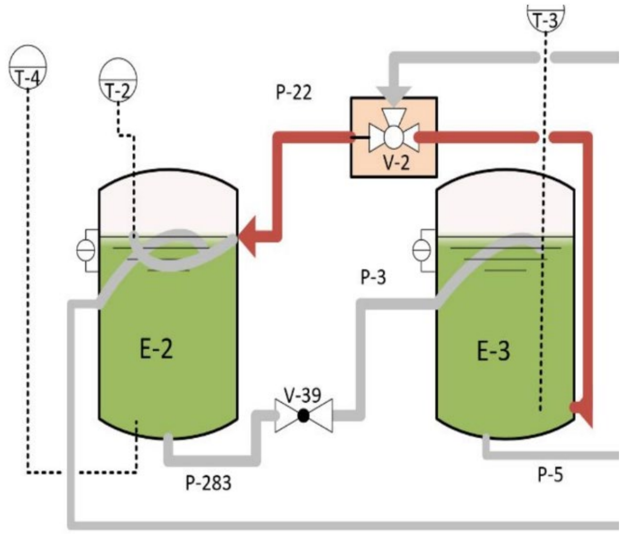

Figure 37: Positions of the desiccant sensors inside the storage tank

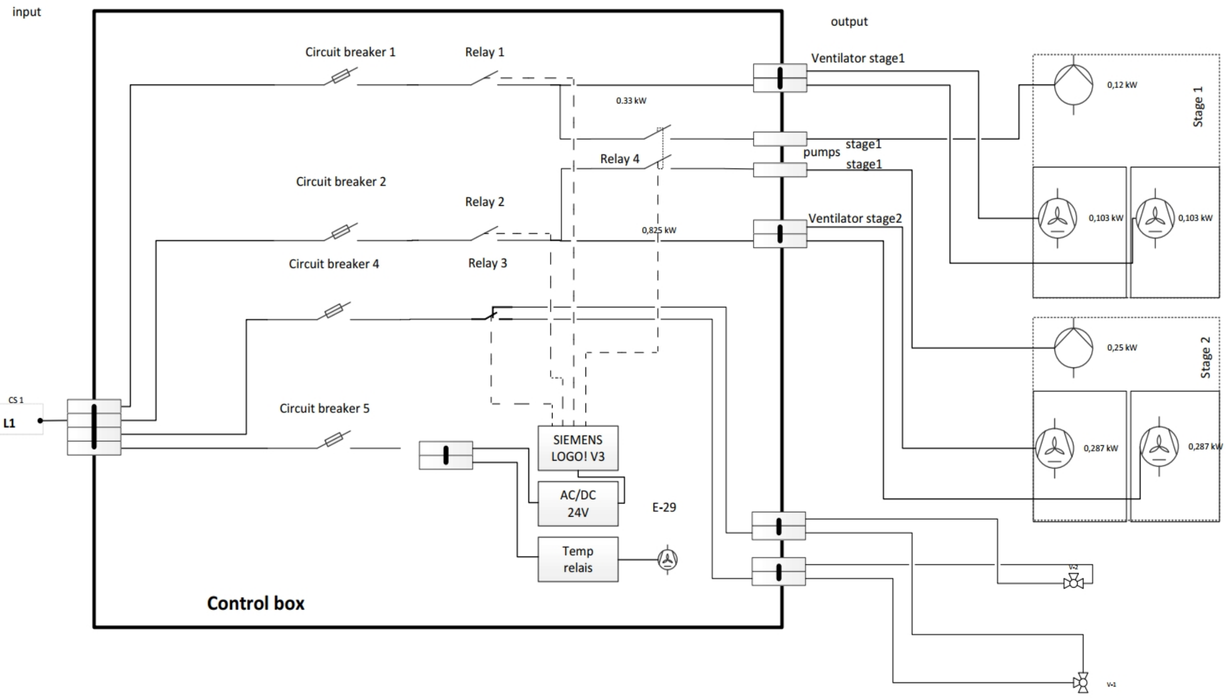

Figure 38: Blueprint of control box with connections to sensors and actuators

This project has received funding from the European Union's Horizon 2020 research and innovation Programme under grant agreement 101000801.

3.2 Measurements and Interpretation of the results

3.2.1 Results from Absorber Component Tests

This section presents the experimental findings related to the operational stage of the greenhouse's brine-based air absorption system with a specific focus on the thermal results of the air flow entering and exiting the greenhouse and later entering and exiting the absorber.

The global results of the whole experimentation period are compiled in Table 4., while Figure 39. and 3.8. illustrate selected results from a period between 19th of August to the 2nd of September 2023. The variation of temperature at the inlet and the outlet of the greenhouse demonstrates the cooling effect of the LDAS during the day, characterized by a temperature gradient that fluctuated between 5.5 and 23.8°C as shown in Table 4. This observed range aligns with predictions from Lychnos and Davies, who studied the performance of LDCS in various locations, including Sfax. Their predictions anticipated a decrease in greenhouse temperature ranging from 5.5 to 7.5°C. The comparison between our experimental results and their predictions further supports the effectiveness of the LDAS in achieving significant temperature reductions in greenhouse environments.

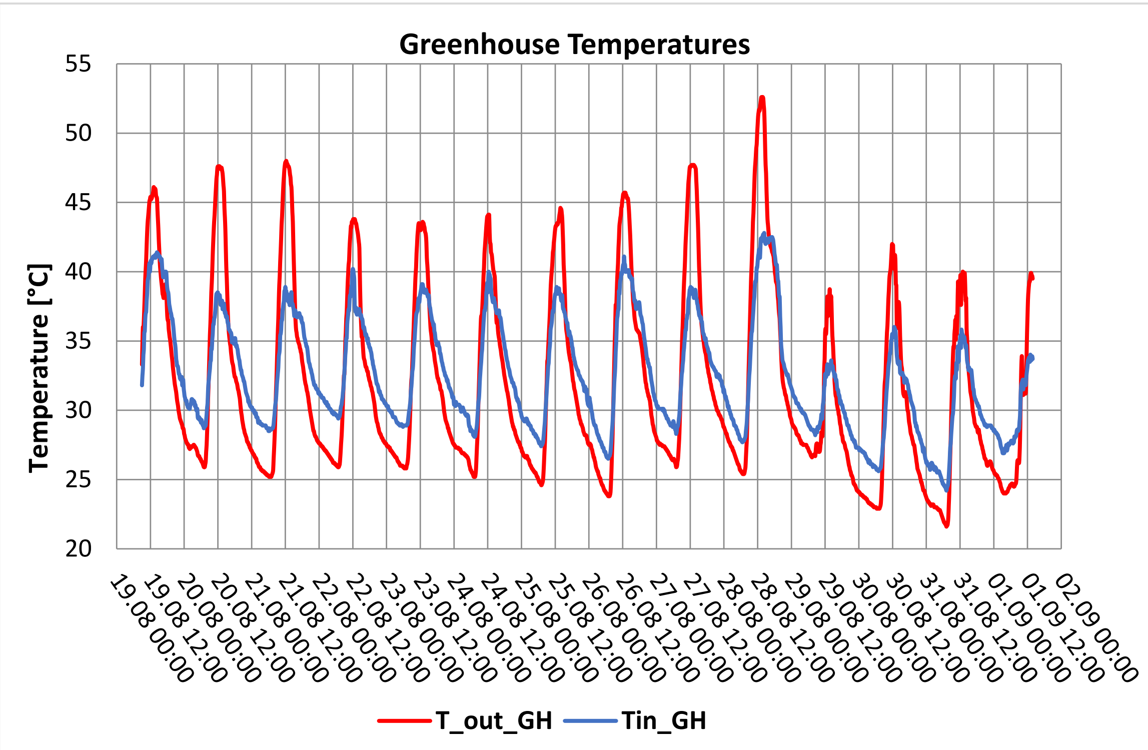

Figure 39: Experimental Results of air temperatures at the inlet and the outlet of the greenhouse, demonstrating the cooling performance of the absorber, which is positioned in front of the air inlet

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Table 4: Experimental Results of greenhouse relative humidities

Month	T_f (°C)	Mean Δ_T (°C)	Max. Δ_T (°C)	Mean Δ_x (g/m^3)	Max. Δ_x (g/m^3)
March/April 2022	31.34	3.02	14.30	11.51	33.36
November 2022	29.95	1.23	5.50	6.50	14.13
March/April 2023	26.14	4.53	23.80	12.18	43.93
August 2023	35.28	2.20	10.80	13.56	32,35

Furthermore, the experimental investigation showcased a decrease in relative humidity during daytime operation of the LDAS followed by a reversed increase during the night, with raising nighttime temperatures as illustrated by Figure 40. The removal of moisture expressed in terms of the specific drying, which is the difference between the absolute humidity of the air flow entering and exiting the greenhouse reached a maximum of 43.93 g/m^3.

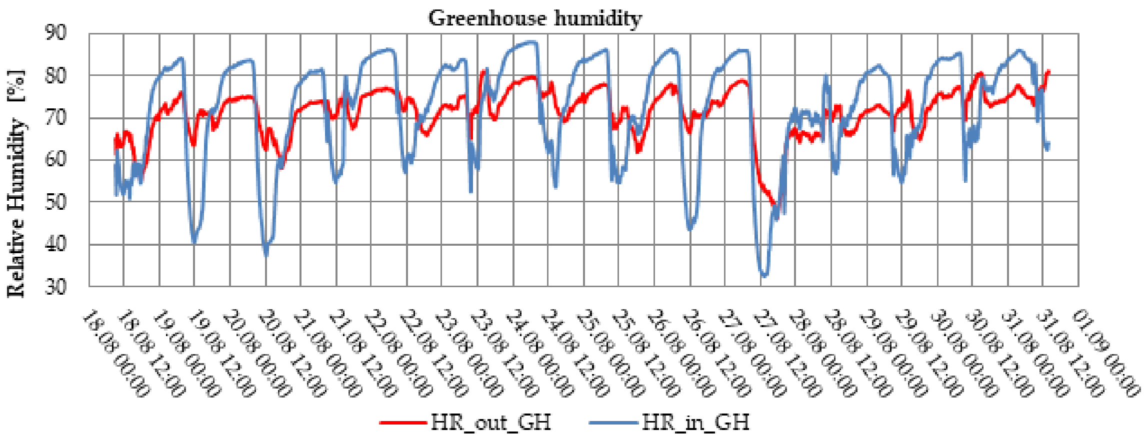

Figure 40: Experimental Results of Relative Humidity at the inlet and the outlet of the greenhouse

The mean specific drying ranged between 6.5 and 13.56 g/m^3. The moisture removed from the humid air flow by the BLD, during daytime operation, is released during nighttime operation of the LDAS resulting in a heating effect inside the greenhouse.

The experimental findings highlight the LDAS's capability to regulate humidity and temperature in the greenhouse, fostering a balanced and controlled environment. However, it is crucial to note that extreme temperature and humidity conditions, particularly on peak overheating days, are not entirely mitigated. Further optimization of the system is imperative to address these challenges and establish a consistently controlled climate conducive to year-round plant growth in the greenhouse.

This section presents the performance evaluation of the Absorber device which is the key component of the desiccant air conditioning system. During the daytime phase, it is observed that the humidity entering the absorber is greater than the humidity exiting it, thereby providing evidence of the dehumidification effect of the absorber.

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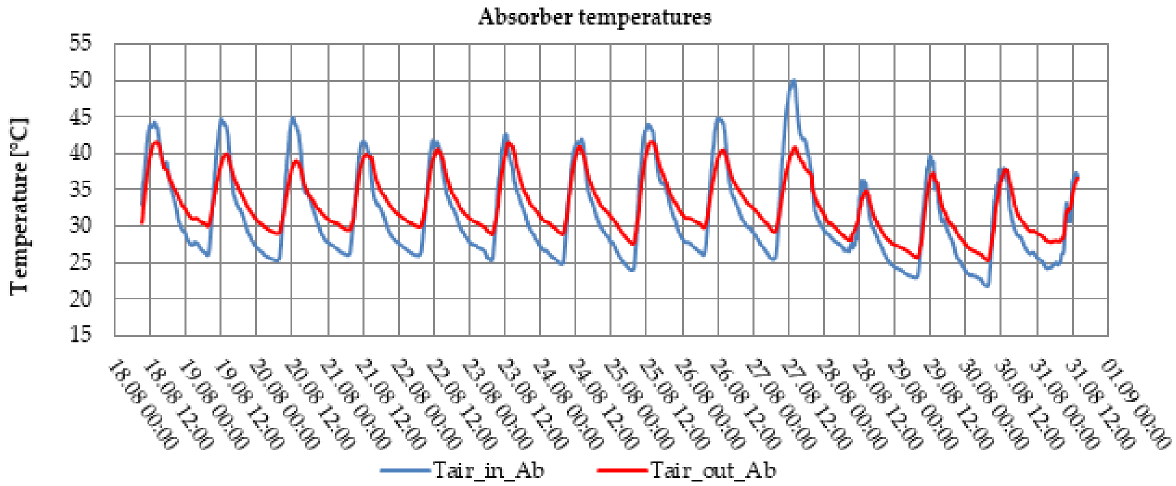

Figure 41: Experimental Results of air temperatures at the inlet and the outlet of the absorber

The results of these experimental investigations will be used to install an advanced absorption climate control system that incorporates multiple absorber devices in a 100 m2 greenhouse at the INRGREF research station.

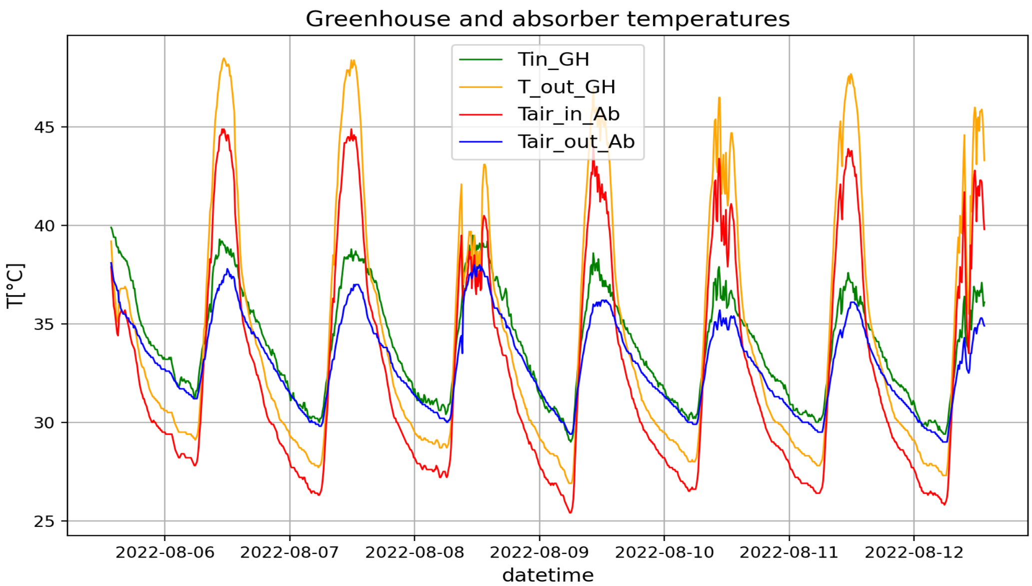

Figure 42: Greenhouse and absorber (In- and Out-) Temperatures

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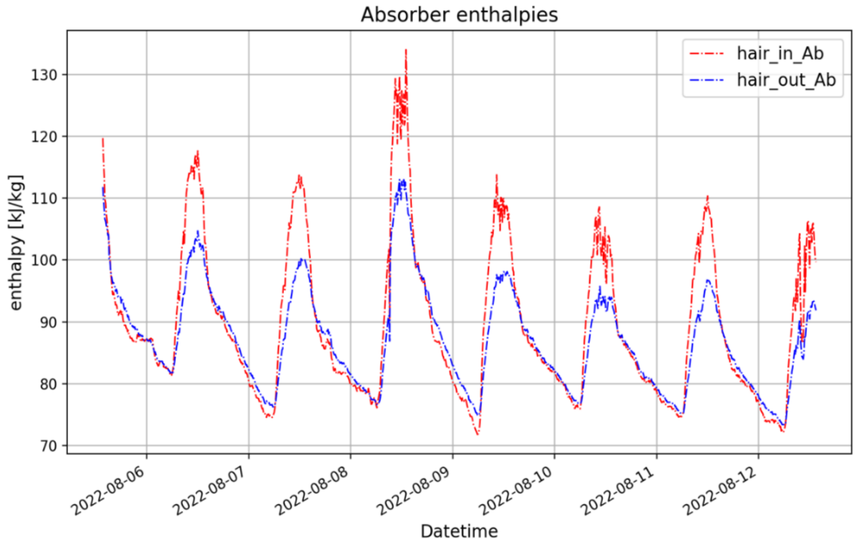

Figure 43: Absorber enthalpies (air energy content including sensible and latent heat)

In Figure 42. is described a situation of temperature in the greenhouse and in the absorber flow (orange and red) and cooling effect by dissipating heat into the storage tank with reduced values in the absorber return flow and on re-entry into the greenhouse (green and blue). At night, the process is reversed and heat from the storage tank is transferred back into the air. In Figure 43. the display of the enthalpy values in the absorber flow and return (red and blue respectively) includes the air humidity measurement and indicates the total energy dissipation (sensible and latent) in the absorber. Another option is the specification in water content (g/kg air), which indicates the return of water vapour into the greenhouse as the basis for the condensation yield (no illustration).

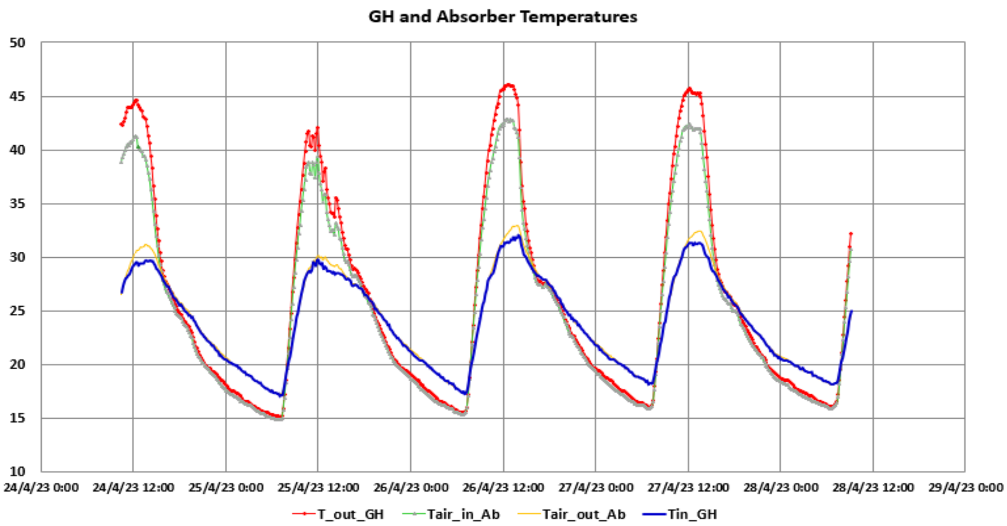

Figure 44: Greenhouse and Absorber Temperatures: A further temperature measurement in April 2023 shows improved heat dissipation via the absorber.

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Berlin Absorber Tests

The tests within the project on the construction of absorbers for the Tunisian greenhouse are aimed at an improved version of absorption devices with the following focal points: (1) improvement of brine distribution on a high number of textile cylinders by using 3D printing; (2) tests with misting devices to optimize uniform air distribution in the absorber and (3) tests with colored liquid to optimize uniform brine distribution. The tests revealed several deficits that were considered when redesigning the absorbers for the Cherfech greenhouse demonstrator.

As a main result from these tests. the further development of the absorber device became a specific focus of the work at TUB and Watergy. In particular, the TCF distribution element (as a 3D print), shown on Figure 45. was improved regarding the required higher volume flow of the solution. A new desiccant distribution system was developed, using internal distribution pipes connected from the bottom of the basin (see Figure 45). In addition, the element was split into three smaller individual parts to reduce the risk of deformation at high temperature. The distribution elements were also optimized for improved brine distribution at high brine flows.

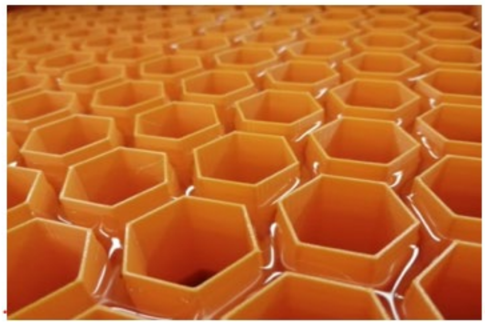

Figure 45: The newly developed arrangement for brine distribution in the absorber enabled both very low, controllable volume flows for pure drying and regeneration processes, but also high-volume flows for the supply and removal of heat via the brine through an even distribution of the brine within the device and the arrangement of openings between the hexagonal overflow tubes.

3.2.2 Results from Heat Exchanger Component Tests

Measuring and analyzing a specific air-to-air heat exchanger aimed at providing additional heat release of greenhouse air to the surrounding air. The air-to-air heat exchanger was seen as an alternative to an enlarged greenhouse surface (as developed in Cherfech), to allow to also to quality conventional greenhouses for closed operation. Also, a part of the condensation yields should be achieved within this element. However, condensation requires very high humidity values in the air flow, close to the dewpoint. Until now, this could only be achieved by operating the greenhouse humidification system very intensively.

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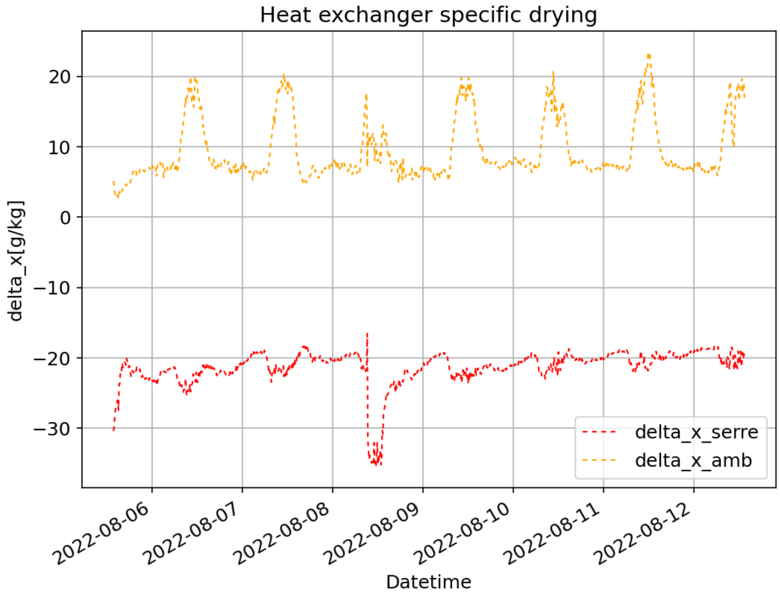

Figure 46: Measuring and analyzing the air-to-air heat exchanger, Example of humidity differences in the greenhouse and outside air flow of the air-air heat exchanger

The main result from these tests was negative. The additional cooling was low, and no condensation was measured. This was understood according to remaining air leakages in the lab greenhouse, but also in the air ducts between the greenhouse and the heat exchanger and leaks in the heat exchanger itself. The air flows from the greenhouse and the outside air apparently mix within the plate structure of the heat exchanger, though a high attention was given to make the sealing of the HE air-poof. By these circumstances, the dew point was only reached in certain short situations. Proof of water yields in normal operation therefore did not appear.

3.2.3 Results from Test of Liquid Desiccant from Tunisian Sailna ($MgCl_2$ /$MgSO_4$ Solutions)

The evaluation of the hygroscopicity of the liquid desiccant derived from seawater brine was measured in terms of its Equilibrium Relative Humidity (ERH). This assessment was conducted under greenhouse conditions in January 2022. The measurement involved determining the RH of air in contact with the BLD, which was then compared to the RH of air in contact with pure water, when equilibrium state was reached. The selected experimental results of RH measured during the 21st of January, depicted in Figure 47. vividly illustrate the dehumidification effect of the BLD.

Experimental findings demonstrated that:

- under greenhouse humidity ranging between 32% and 75%, ERH fluctuated between 20% and 36%.
- under high greenhouse RH, exceeding 85%, ERH ranged between 27% and 35%, while water maintained the RH of the air at the range [45%; 76%].

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The obtained results reveal an ERH range of 20% to 36% with a mean value of 29.86%, underscoring the commendable hygroscopicity of the utilized BLD in the greenhouse air conditioning system. The ERH, a property of prime importance of the BLD, and low values are recommended in desiccant cooling systems to achieve desirable wet bulb temperatures [33].

The experimental results showcasing a mean value of ERH at 25°C of 29,95 ≈ 30%, revealed a commendable ERH range, notably, when juxtaposed with the findings of the experimental investigation conducted by Lychnos et al., to evaluate the hygroscopic properties of a similar liquid desiccant of a density of 1330 kg/m^3, derived from seawater brine obtained from Salina Sfax [39]. The BLD studied in the present work, despite having a slightly lower density (1324 kg/m^3), exhibits a substantially lower ERH value of approximately 30% compared to Lychnos et al.'s reported 37.4% at 25°C.

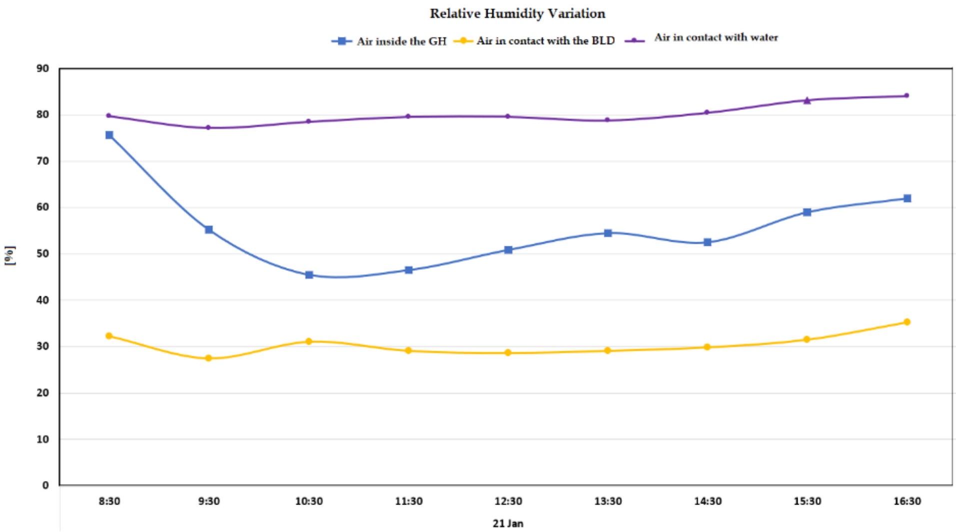

Figure 47: Experimental Results of ERH and RH measurements

Table 5: Main chemical properties of the desiccant solution.

Designation	Value	Unit
Density	1324	kg/ m3
Concentrations:		
Magnesium (Mg)	112.65	g/L
Sulfate (SO4)	34.09	g/L
Chlorine (Cl) and Residues (Ca, K..)	428	g/L

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Furthermore, the measured values of ERH are in accordance with established literature referencing ERH value of 32.78 ± 0.16% for pure saturated $MgCl_2$ solution at 25°C. Notably, the BLD used in our system, contains in addition to Magnesium chloride, impurities such as sulphate, sodium, potassium, and calcium (as detailed in Table 5). Given the nuanced impact of density, specific composition, and impurities' characteristics on the hygroscopicity of the liquid desiccant, the studied BLD might exhibit a higher ERH compared to pure diluted $MgCl_2$. However, our findings reveal a lower ERH value for the BLD. This unexpected result adds an interesting dimension to our study, suggesting that the BLD, despite its impurities, demonstrates a more favourable performance in greenhouse air-conditioning applications than anticipated.

3.2.4 Results from the Cherfech Greenhouse Demonstrator

Simulation results and initial measurement of greenhouse stagnation temperatures:

A comprehensive greenhouse model was created during the planning phase of the project, based on the Python programming environment. This includes modules for solar radiation, site-specific data, a building model that contains the greenhouse geometry (including the Zigzag shape of the walls) and the usable material properties. Furthermore, heat sinks (soil, storage), air humidity models (latent energy flows through vegetation) were built. The result is indicated on Figure 48 for a period of three days using general climatic data of Tunis. The planned components for mechanical greenhouse cooling and air dehumidification were built. A model for an absorption process with the sorption solution magnesium chloride is being developed based on measurement results from previous projects.

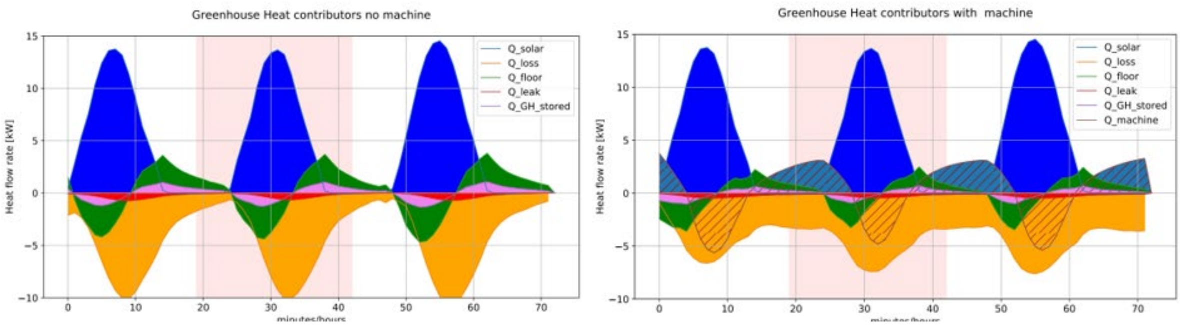

Figure 48: Simulation results from the planning phase as a base for the data analysis. Left shows the energy solar input and energy dissipation through the foil (yellow) into the soil (green) and minor leakages and losses (red). Right shows the system with an additional dissipation to a themal storage through an absorber (hatched surface), providing a shift of energy dissipation from daytime to nighttime.

The simulation of the greenhouse system without climate control indicated strong over-heating of the greenhouse with temperatures up to 50°C and related high heat transfer to the air ambient. The related energy balance is indicated on the left picture with the yellow surface indicating high

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daytime peaks. In the second figure, a climate control system, taking out a part of the heat energy (sensible and latent heat) to an additional heat storage was simulated, leading to a different energy balance with lower temperatures and accordingly lower heat transfer to the environment (daytime operation, right figure). The additional heat pathway to the storage is indicated with the hatched surface. Unloading of heat from the storage with higher heat transfer to the ambient is indicated during the nighttime operation (larger yellow surface between the peaks).

The simulation model was gradually being developed further and verified/calibrated with data obtained from test runs in the Cherfech Demonstrator as indicated on Figure 49 for a period of five days(13th to 18th of June 2023). Mobile data loggers were used to measure the temperature curve in standstill mode, providing stagnation temperatures at different levels of the greenhouse including underground measurements in 10, 20 cm depth. The results confirmed the model.

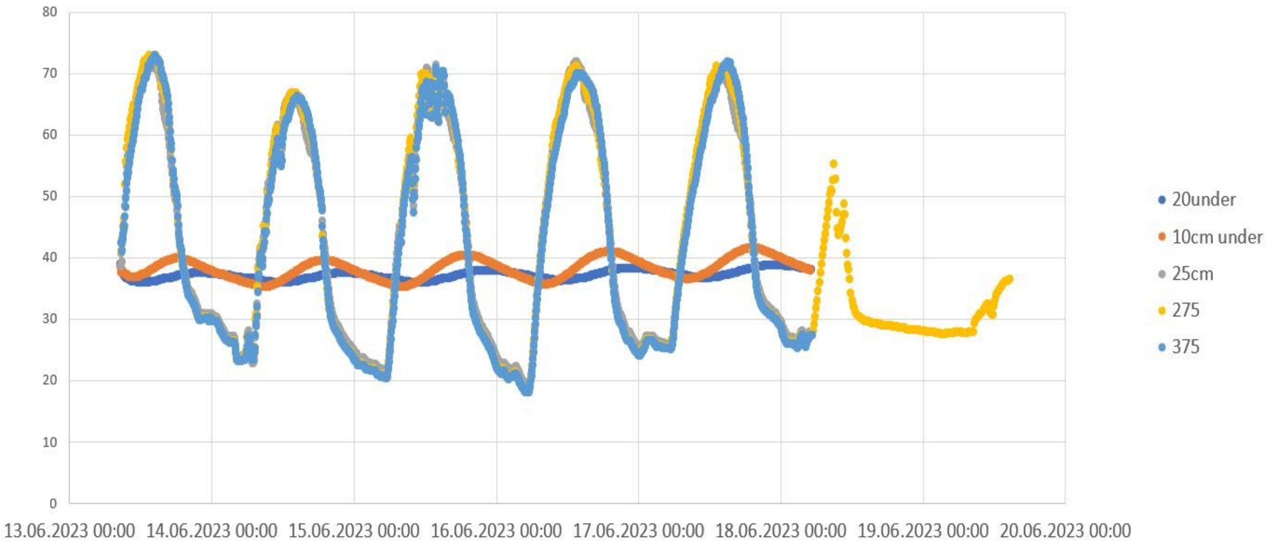

Figure 49: Temperature measurements in the greenhouse during 5 days in April (grey yellow and light blue) and soil (blue and orange) show high stagnation temperatures during daytime and low storage capacity of dry soil, leading to lowered heat release during night.

Cherfech Greenhouse Demonstrator: Measurement period March / May 2024:

Initial measurements in the greenhouse including testing the basic functioning of all components, (actuators and sensors) and identification of any necessary system adjustments was performed during March and April 2024. These measurements prompted several adjustments, significantly enhancing the system's performance from its initial vague state. However, the very hot summer period started unusually early in 2024, limiting the system's performance opportunities since it was not designed to operate during the hottest part of the year.

As a main result, the malfunctioning of the storage was identified. The brown curve in Figure50 indicates the temperature development in the greenhouse on *18th of March. A* cooling period

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performed by the installed absorber during midday (area between the peak temperatures) shows a clear decrease of temperature with values around 35°C provided by the cooling system. However, while the cooling effect was evident, the storage only responded by a slight temperature rise of the storage upper level (black line) from 26 to 30°C, while the middle level (blue line) and bottom level (purple line) did not show any respond but stagnating temperature. Therefore, the storage valves were analysed for malfunctions. Only a small quantity of desiccant around the top level was circulated, while the storage heat reservoir was not used. The valve repairs took some time but resulted in proper functioning.

Also, it was analysed that the system stopped too early, leading to the second peak of the temperature in the afternoon. As a result, the temperature set points for the different cooling modes were raised to provide a more constant cooling period. Also, the set point for emergency ventilation and adequate system shutdown was increased, to allow a full-time daily cooling period and to be able to continuously run the system during the day, even on hot ambient conditions.

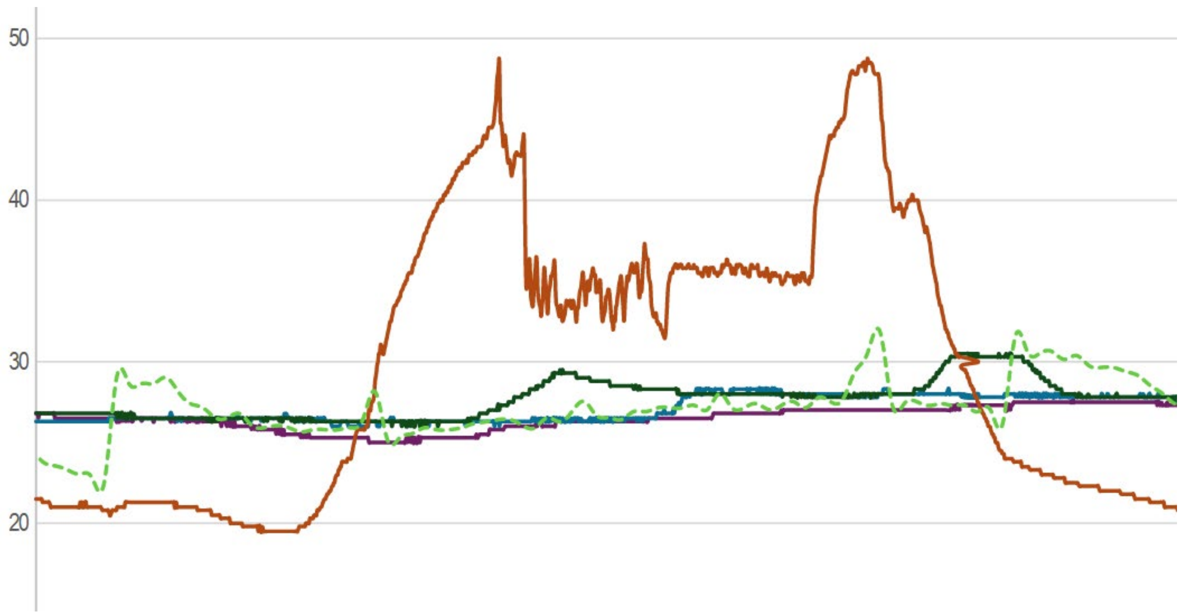

Figure 50: First measurements for system adjustment at the Cherfech Demonstrator climate control system on the 18th of March showed a malfunctioning of the storage valves, that could be repaired as an adjustment measure.

Measurement period in May

Greenhouse Cooling and Storage over Three Days: The set points for the control were raised to higher values compared to the initial tests, so that the system would shut off later. In that way, higher temperatures in the storage could be reached during the day, due to higher supply temperatures from the greenhouse air.

On the first day, the weather was very hot with ambient temperatures up to 45°C. The new settings of the control let the system run until the GH-temperature reached ~48°C. Unfortunately, this was already

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the case at noon (12:12 h). A sudden temperature increase was identified, showing a missing performance capacity of the system for this climatic situation.

The absorber performance for the humidity control was sufficient with values below 60% greenhouse air rel. humidity. Further improvement is still required for the sensible heat transfer in the absorber. We have a desiccant temperature of 32°C coming from the storage but we can cool down the air only from 45 to 42°C. The desiccant takes up around 20kw of sensible heat. For a sufficient cooling at this stage of the year and a given heat wave, the cooling performance should almost be doubled. Increasing the desiccant flow rate is not an option and would probably not help, as the storage volume would recirculate. We should look inside the absorber to find out why we are so far away from the thermal equilibrium.

The storage middle sensor and storage bottom sensor were switched. This was corrected during an update of the control programme.

Looking at the whole period, it is also visible, that the storage temperature is rising over the days. It is shown that the system underperforms, as we do not get sufficiently rid of the heat during the night. There shall be more stage 3 with high volume flows during the night. But even in stage 3 we can only get rid of 10 kW of sensible heat during night.

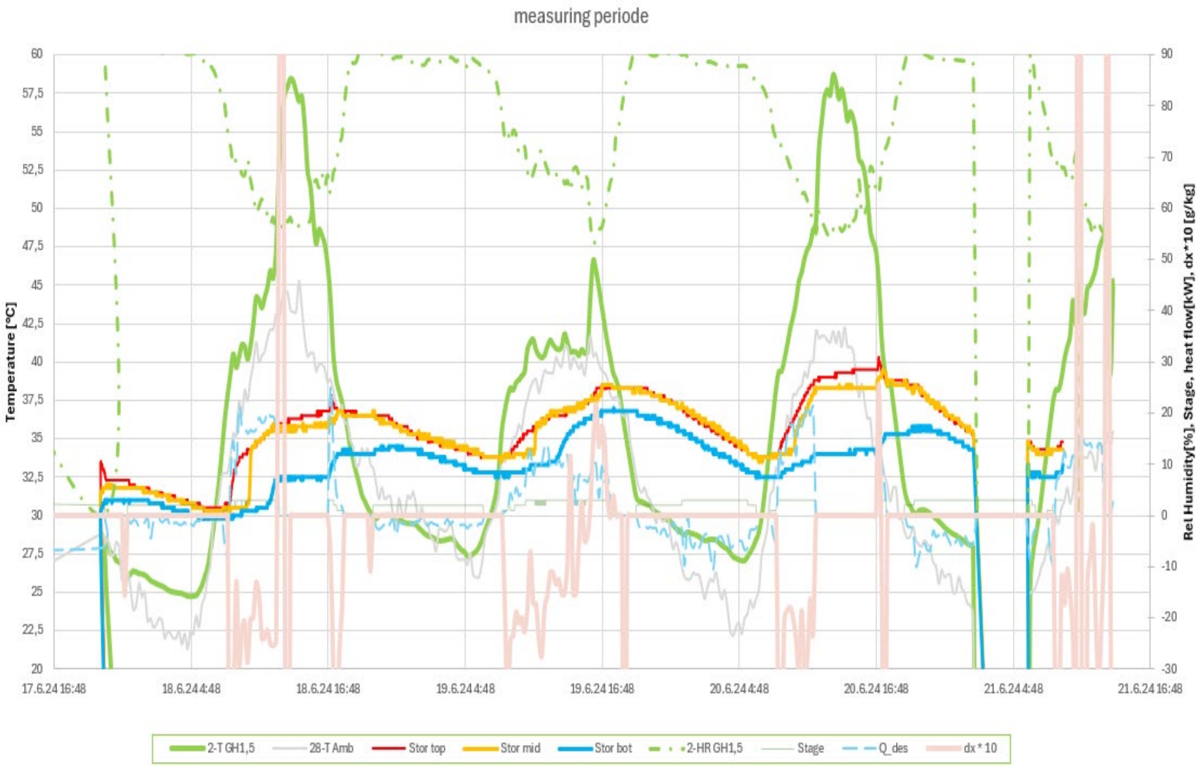

Figure 51: Three-day period of greenhouse cooling and storage development: Green line (greenhouse air temperature) in compariston with storage temperatures (Red = top level, Yellow = mid level, blue = bottom level

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Figure 51 shows a three-day period, in which only the second day provided a running cooling system. On the first day, the system shut down at greenhouse temperatures (green line) above 45°C. However, also this was the hottest day with related ambient max. temperatures of 45°. Looking at the development of the three storage temperatures (red/top, yellow/middle and blue/bottom), a sudden increase of the yellow and the blue curve confirms the delay of the storage temperature development during operation.

The regeneration (cooling) of the storage is still insufficient. The initial temperature level from the first morning is not reached after the nighttime de-loading periods. The storage cools down but slightly heats up over the days. Insufficient cooling of the greenhouse daytime and storage nighttime is part of the same problem: An insufficient functioning of the absorber. The element must be removed and analysed. It looks, as the desiccant flow is unequal and a larger part of the fluid passes the device without sufficient contact to the air.

Morning Greenhouse Cooling with Noon Shutdown: Figure 52 shows a good functioning of the cooling system until midday with air temperatures from the absorber (red) keeping down the greenhouse temperature (green). Afterwards, the cooling stops (improper pumping from the storage) and the temperatures in the absorber show stagnation temperatures. Emergency ventilation seems to start an hour later, then keeping the greenhouse temperature at around 55° with ambient temperatures around 45° being insufficient for a proper cooling effect. It is interesting to see the good performance of the cooling system before noon compared to the insufficient cooling with ventilated air exchange (emergency ventilation). The local state of art cooling with passive (wind driven and/or buoyancy driven) ventilation must be even worse.

Top and mid-level of the storage rise from 30 to 35 °C during the morning, while the bottom level remains unheated. This is an indication for an unused cooling capacity, that would justify a longer cooling period at the state of improved system control. The stop of the system at midday is probably caused by improper setpoint selection of maximum temperatures.

Advanced System Control: Figure 53. shows a full day of performance. The storage bottom temperature starts increasing at around midday. This demonstrates a good dimensioning of the storage for a full daytime period, providing cool from the deeper level for the afternoon period. Storage temperatures start from 32/33°C and rise to 36/38°. The storage performance is lower than expected with insufficient maximum temperature values. Higher values are required for good results in desiccant regeneration. An improved absorber functioning, gained by further improved equalisation of the desiccant flow over the entire exchange surface, could help to increase the desiccant temperature coming out of the absorber (pink dotted line). In this case, absorber temperatures should be at least slightly above the greenhouse air temperature due to the heat released by the absorption process.

A higher storage temperature would lead to higher desiccant concentrations during the nighttime regeneration process and again would produce higher temperatures in the absorption day times by gaining more heat from the phase change effect.

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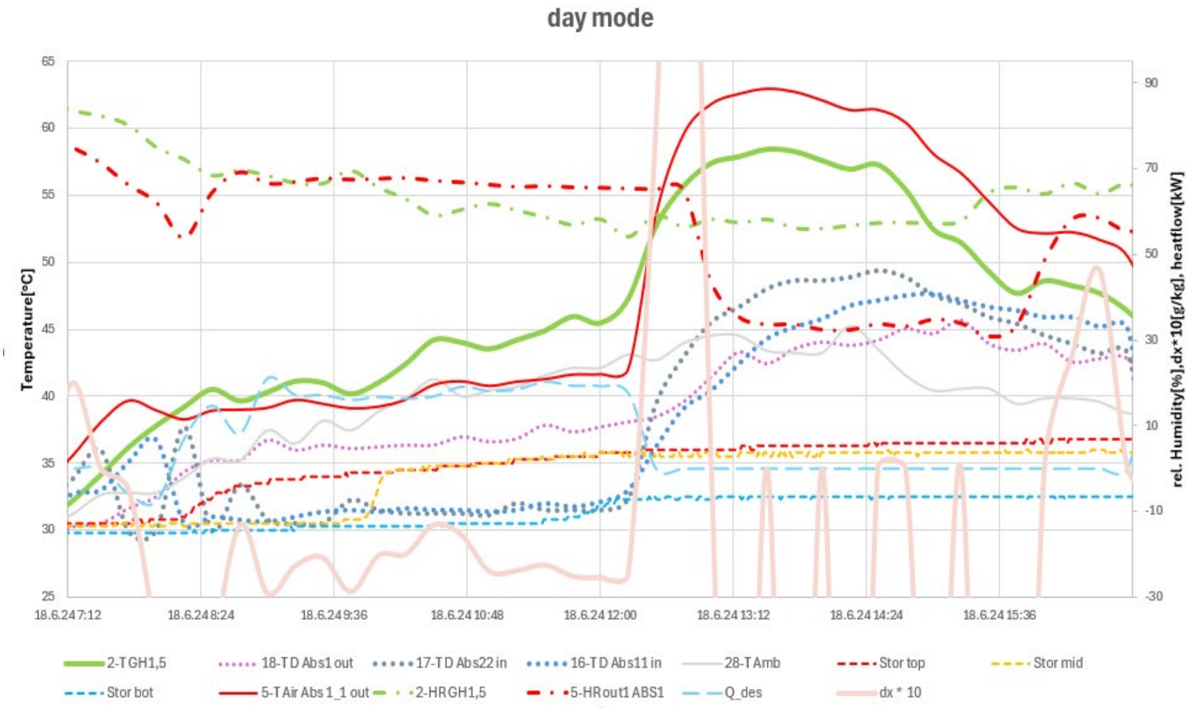

Figure 52: Greenhouse cooling at morning period with sudden stop at noon: The desiccant temperature at the absorber outlet (red) is clearly below the greenhouse temperature (green line), indicating a proper cooling effect. Storage temperatures are indicated as deshed lines (red=top, yellow middle, light blue = bottom

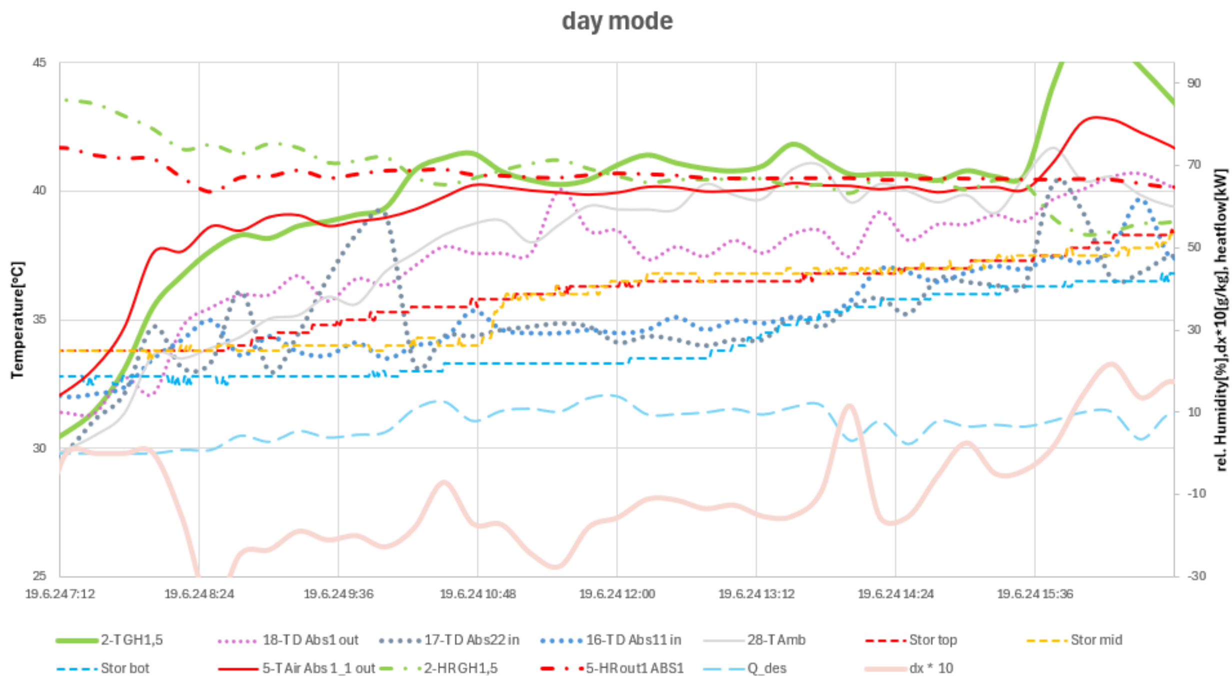

Figure 53; Advanced system control through almost the whole day, keeping the indoor temperature (green line) at around the ambient temperature (light grey line).

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However, the greenhouse humidity is below 70% and follows the values from the absorber air outlet. This is already a lower humidity than in many greenhouses with insufficient aeration. It will allow lower air temperatures within the vegetation canopy due to the improved evaporative cooling performance of the crops. Values here should also be measured and further investigated.

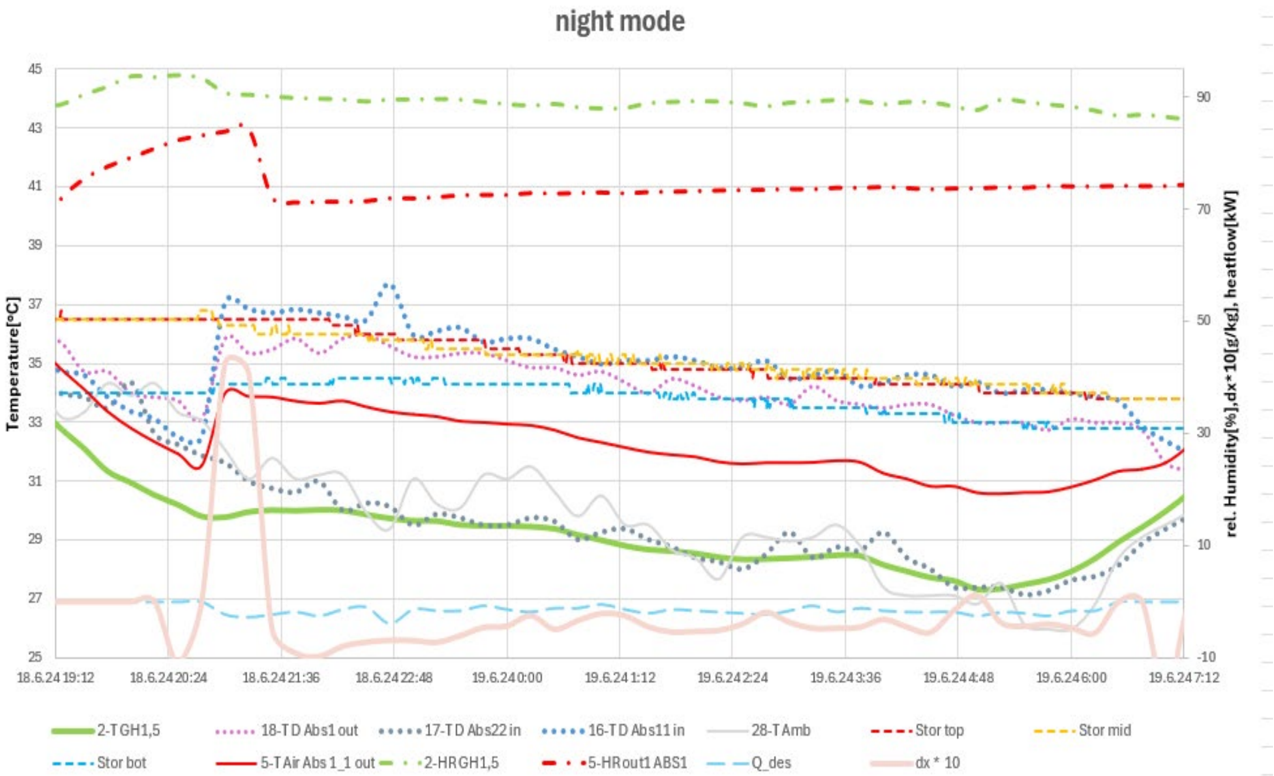

Figure 54: Example for nighttime operation with storage de-loading (decreasing temperatures at the storage, indicated as dashed lines (red=top, yellow middle, light blue = bottom) and related, heat energy consuming desiccant regeneration function

Nighttime Operation: In Figure 54, the night operation mode switches at around 8:30 pm. The cooling process improves around 10pm due to ambient temperatures below 30°. The bottom zone of the storage is still slightly heating up at this time of the day, due to mixing effects from the top level. The storage temperature decrease is only in the range of 4 K until 7 am and maybe further cools down until 8 (not part of the measurement). The absorber air outlet temperature (red) is around 4K above the greenhouse temperature (green), so there is a clear heating effect during nighttime.

A greenhouse air humidity of around 90% is a good prerequisite for condensation. However, the greenhouse temperature is close to the ambient temperature due to the remaining weak heating of the storage in daytime. In this way, condensation may not appear at the inner surface of the roof under these conditions. A better functioning of the absorber would provide more air heating and more water evaporation from the desiccant, providing a better prerequisite for condensation.

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3.3 Conclusions

The basic functions of the sorptive air drying and air-cooling system were investigated and demonstrated in various individual tests and in several control constellations. Complete greenhouse operation over an entire vegetation period could not be carried out due to various problems and obstacles (delays in the construction process, early heat waves caused by climate change and technical obstacles in the operation of the systems, especially in the hydraulics).

Especially, the absorber shall be further observed and improved. During operation, flows of desiccant going around the absorber surfaces were observed. This results in inefficiencies due to the uneven temperature and concentration of the desiccant. The fluid passing the surface and contacting the air mixes with the desiccant bypassing the system, lowering overall efficiency.

The fact that greenhouse cooling with the existing system is possible even at ambient temperatures up to 45°C and an insufficient absorber performance already demonstrates the high potential of the overall system. Considering a better absorber performance, the storage volume looks already oversized in the actual configuration. With higher temperature differences, a lower volume might be sufficient, which is interesting as it constitutes one of the major cost items in the system. With more delta t between day and night, also the use of PCM materials in the storage could be considered, opening the perspective of a volume reduced by factor 3-5, which would be 3-5 m³ instead of now 15. A completely different situation.

Given the high potential for specific solutions in addressing global water supply challenges, the project's partial results underscore the need for ongoing system improvements and continued work after the project ending. Immediate action is requested to maintain the operating of the pilot facilities and to follow-up the ongoing activities. To ensure ongoing growth and application of acquired knowledge, ensuring sustained employment at partner institutions is crucial, presenting a significant challenge.

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