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TheGreefa

Thermochemical Fluids in Greenhouse Farming

TRAINING MANUAL

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1. Introduction

This document presents structure and outcomes of TheGreefa project (Horizon 2020 R&I Programme, Call LC-FNR-06-2020, Grant Agreement no. 101000801), and provides an overview of its main phases and achievements.

1.1. Consortium

TheGreefa is a research and innovation project funded by the European Commission and realised by 12 partners from 7 countries (Fig. 1). The consortium, a team of research institutions, SMEs, agricultural operators and legal experts, has been formed to ensure a balance of skills and expertise for the development of a cost-effective and innovative technology which will significantly reduce the use of fossil energy in agriculture.

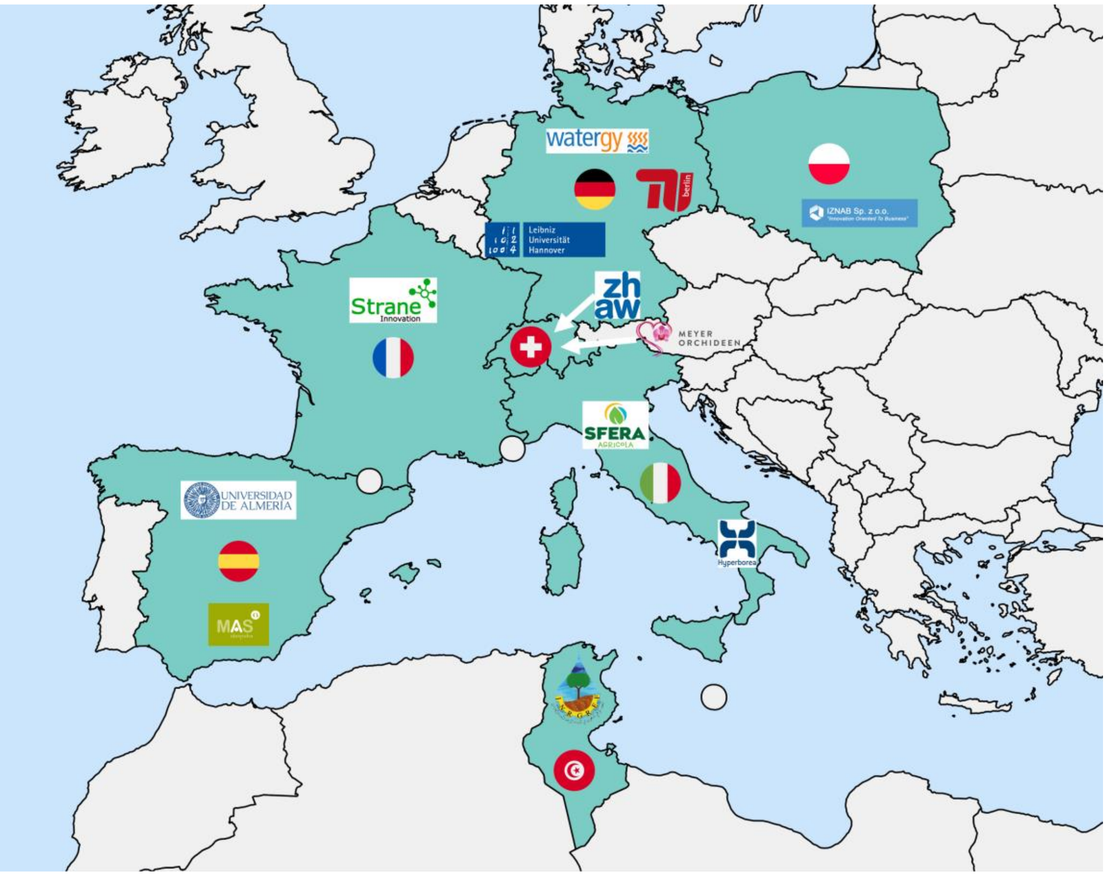


Figure 1. TheGreefa consortium partners

1.2. Project outlines

The scope of the project is the development and testing of a cost-effective and innovative technology which will significantly reduce the use of fossil energy in agriculture.

The proposed solutions of TheGreefa directly align with the EU's key objectives to increase the use of renewable energy by agriculture, where greenhouses are assuming more and more importance. In the developed countries a high quality of life concerns especially the diet, which must be fresh, healthy and varied. Long transport routes are often necessary. The transport of fresh fruit and vegetables causes high CO_2 emissions and a significant proportion of the food's environmental footprint. The poor regions with adverse conditions for cultures cannot afford the import of food.

For both cases, the greenhouses with dryer and water recovery will represent the right solution as long as they satisfy the following requisites as TheGreefa does.

1.3. Concept

The focus of TheGreefa is on applications for greenhouses and for drying processes. The greenhouse technology includes applications for greenhouse climate control, including heating, cooling and air humidity control. The proposed technology uses liquid desiccants, so-called Thermo-Chemical Fluids (TCF). Typical TCFs are salt solutions based on sodium hydroxide or magnesium chloride. The common effect in all applications is the hygroscopic properties of the TCF, allowing uptake of water vapour from the air thus also releasing sensible heat converted from latent heat stored in the vapour. To give an approximation of the process:

- 1 ton of air humidity absorbed into the TCF, according to the phase change involved in energy, releases 680 kWh of heat (right part of Figure 2). The humidity is then condensed to liquid water.
- The uptake of water dilutes the TCF. When the TCF is diluted to a certain degree, the process cannot be continued and the TCF must be regenerated. The absorbed water must be driven out again.
- For the re-concentration (regeneration), the same amount of energy as released by the absorption process shall be reintroduced in the system, again appr. 680 kWh/ton of evaporated water. Temperatures below 60°C of the heat source are largely enough for the regeneration process, the exact temperature depends on the phase equilibrium of pressure vapour between the TCF and ambient air.

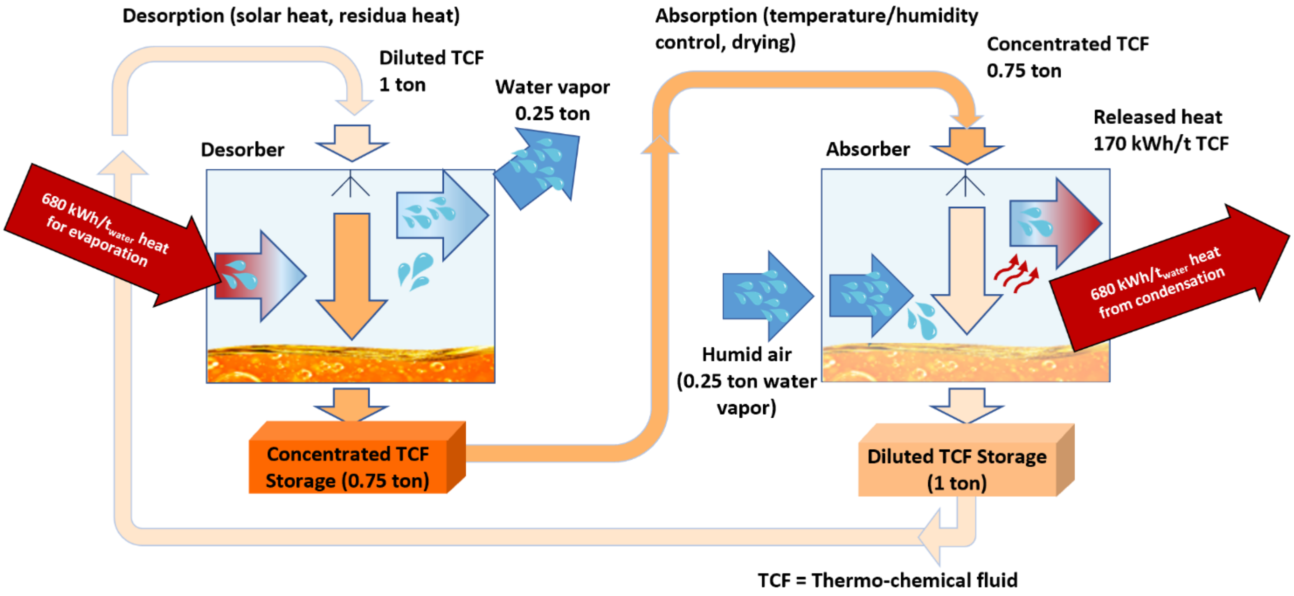


Figure 2. TheGreefa concept.

The water can be released in the form of water vapour taken up by dry air (left part of Figure 2) or can be condensed and recovered as pure water.

The diluted TCF can be stored and regenerated when the heat is available, for example during sunny days with solar energy or by residual heat. The concentrated TCF can the stored in simple plastic containments (e.g. IBC-tank for small applications) for as long as necessary, for example as seasonal storage. The shift in time and space between the regeneration process and the effective use of the TCF is the big advantage of the proposed solution in comparison with existing sorption processes for example desiccant rotary wheels.

In regeneration mode, the process can be operated with a humidification- and (evaporative) cooling effect as additional service.

1.4. Application for greenhouses

Greenhouse heating is the most relevant cost factor for the greenhouse business in Central Europe. TheGreefa can be applied successfully in those regions reducing the energy amount required for heating.

This application is explained in Figure 3 below, which compares the energy and water flows of a standard greenhouse (left) with a greenhouse where the proposed technology is installed (right).

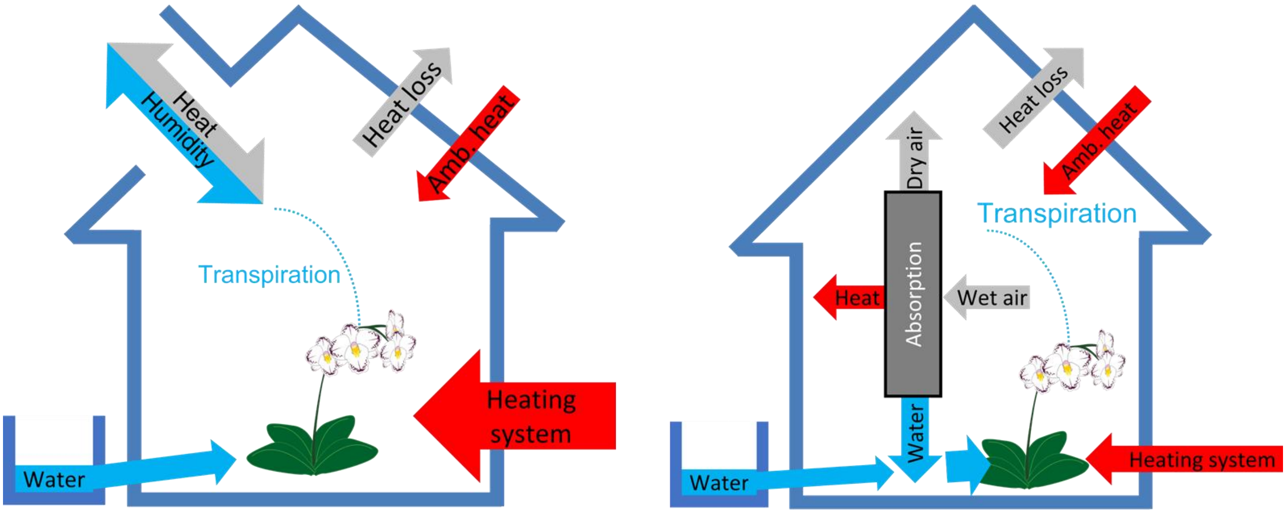


Figure 3. Application of the technologies in greenhouses – standard greenhouse (left) and the proposed technology (right).

The total energy consumption (red arrows) will be strongly reduced: on one side there will be a zeroing of the heat loss for ventilation because the air is recirculated, and the humidity removed by the TCF. On the other side, heat is released through the absorption process.

The technology consists of an open counter-flow heat and mass exchanger (absorber), which dehumidifies and heats/cools down the air under the use of TCF by absorption. The absorbed water can be recovered as pure water. The thermal heat can be seasonal stored in form of concentrated TCF. There is and a time- and place-shifted recovery of the thermal heat.

1.5. Application for drying process for food preparation

The process is also very suitable for the drying of agricultural goods like herbs and fruits, which must be dried immediately after harvesting regardless of the weather conditions.

This application is explained in Figure 4. The air is dried in an absorber in counterflow with a concentrated TCF but is not necessarily heated, as heat could harm the leaves/vegetables and affect their quality. In a closed cycle, the released dry air is then injected into the dryer chamber where the humidity of the vegetables can be extracted. The diluted TCF can then be stored without thermal loss and regenerated when renewable heat (e.g. solar heat) is again available. In comparison to the state-of-the-art plants using compression dehumidifiers, in a sorptive dryer, the electrical energy consumption is limited to the operation of fans and liquid pumps, while the thermal energy required can be entirely provided by a low-temperature heat source, e.g. can be renewable (solar heat, waste heat). After the regeneration process, the energy provided also can be stored without any losses in form of concentrated TCF.

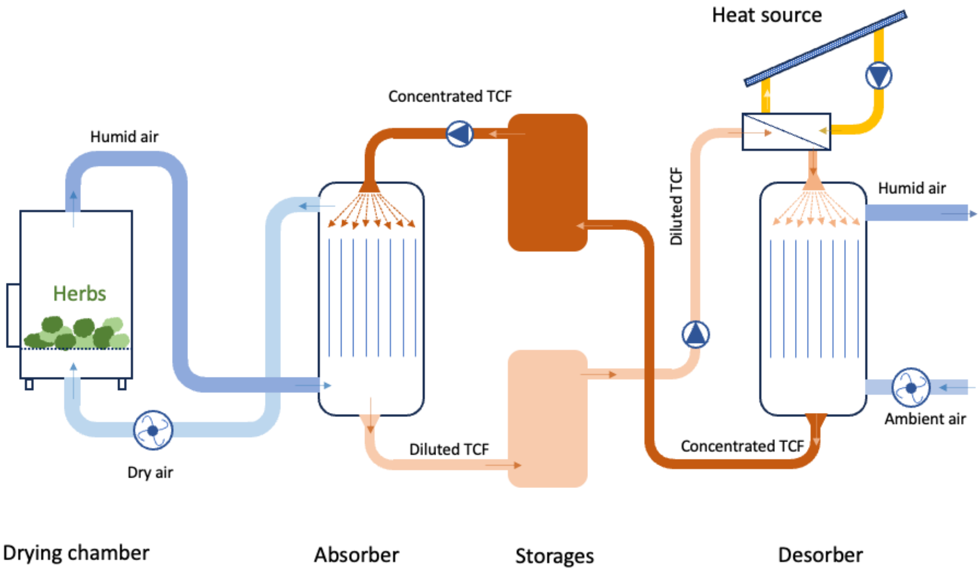


Figure 4. Drying process with the use of absorber and desorber.

1.6. Regeneration of the TCF

After the absorption, the thermochemical fluid has reached the saturation point and is then insufficient for drying/dehumidification purposes. The TCF needs to be regenerated to release the absorbed water. The regeneration is the opposite process of the absorption. The TCF is taken in contact with dry air and parts of the water from the TCF solution is evaporated to air passing through the device. To force the process, a small amount of heat at a low temperature usually is necessary to increase the air temperature, thus decreasing its relative humidity. The temperature level depends on the vapour pressure equilibrium between air and TCF, in any case, it will be below 60°C. The "heat" is stored during this process inside the TCF in the form of thermo-chemical potential (concentrated TCF).

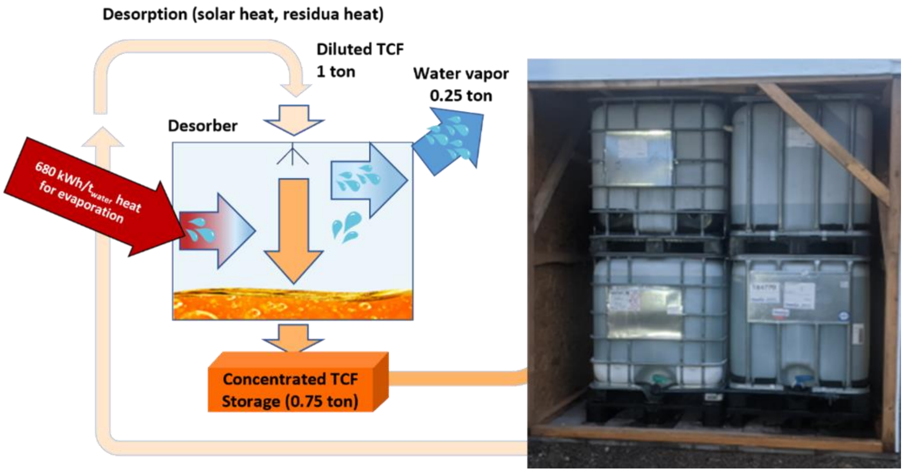


Figure 5. TCF regeneration.

The absorption and desorption could take place in the same column (called absorber) in different periods. The vapour pressure equilibrium between air and TCF will determine in which direction the water/humidity will flow.

1.7. Fluids utilised in TheGreefa

The thermochemical fluids used in this project are $MgCl_2$ and NaOH.

MgCl2 is not very commonly used in drying processes because its hygroscopicity is much lower than the hygroscopicity of LiBr or LiCl; $MgCl_2$ solutions can reduce the relative air humidity to 30% at ambient temperature (20°C), but not below. However, the required humidity for greenhouse application is in the range of 40-70%, which means the hygroscopicity of $MgCl_2$ is sufficient.

The advantage of $MgCl_2$ is its high availability as it is part of seawater with a concentration in seawater of 1 kg/m^3, and the very low cost, which is approximately 100 €/m^3.

NaOH is used for drying application. The MgC_{l2} is not suitable due to its low hygroscopicity. For crop drying, the humidity of air shall be reduced to approx. 10% at the absorber outlet. This is possible using NaOH, whose availability is also high as well as the cost is low. A limit to the use of NaOH is its reaction with CO_2 contained in the air. This reaction does not impact in a significant way the drying process because the air is recirculated in a close loop absorber-drying chamber.

These two thermochemical fluids are harmless: $MgCl_2$ is a product of the salt preparation for cooking, while NaOH is used as an ingredient for special bred preparation.

2. Demonstration of TheGreefa technologies

As already introduced in section 1.3, TheGreefa uses liquid desiccants, so-called Thermo-Chemical Fluids (TCF). Typical TCFs are salt solutions based on sodium hydroxide or magnesium chloride. The common effect in all applications is the hygroscopic properties of the TCF, allowing uptake of water vapour from the air thus also releasing sensible heat converted from latent heat stored in the vapour. To give an approximation of the process:

- 1 ton of air humidity absorbed in the greenhouse, according to the phase change involved in energy, releases 680 kWh of heat. The humidity (vapor) becomes liquid water. The effect is that the greenhouse is heated and dehumidified at the same time
- The uptake of water dilutes the TCF. When the TCF is diluted to a certain degree, the process cannot be continued and the TCF must be regenerated. The absorbed water must be driven out again.
- The diluted TCF can be stored for a long time without any losses, the diluted TCF will be regenerated, when heat is available.
- When heat is available, for example during sunny days or when residual heat is available, the diluted TCF is transported to the regeneration, which can be in the same place of the greenhouse or also in another place (left part of Figure 6 below) because there are not losses during the transport. No thermal energy is stored, but the potential to release thermal energy.
- For the re-concentration (regeneration), the same amount of energy as released by the absorption process shall be reintroduced in the system, again approx. 680 kWh/ton of evaporated water. Temperatures below 60°C of the heat source are largely enough for the regeneration process, the exact temperature depends on the phase equilibrium of pressure vapour between the TCF and ambient air.
- The water can be released in the form of water vapour taken up by dry air or can be condensed and recovered as pure water (central part of Figure 6).
- The concentrated TCF can be stored as long as it is necessary, and also for a long period.

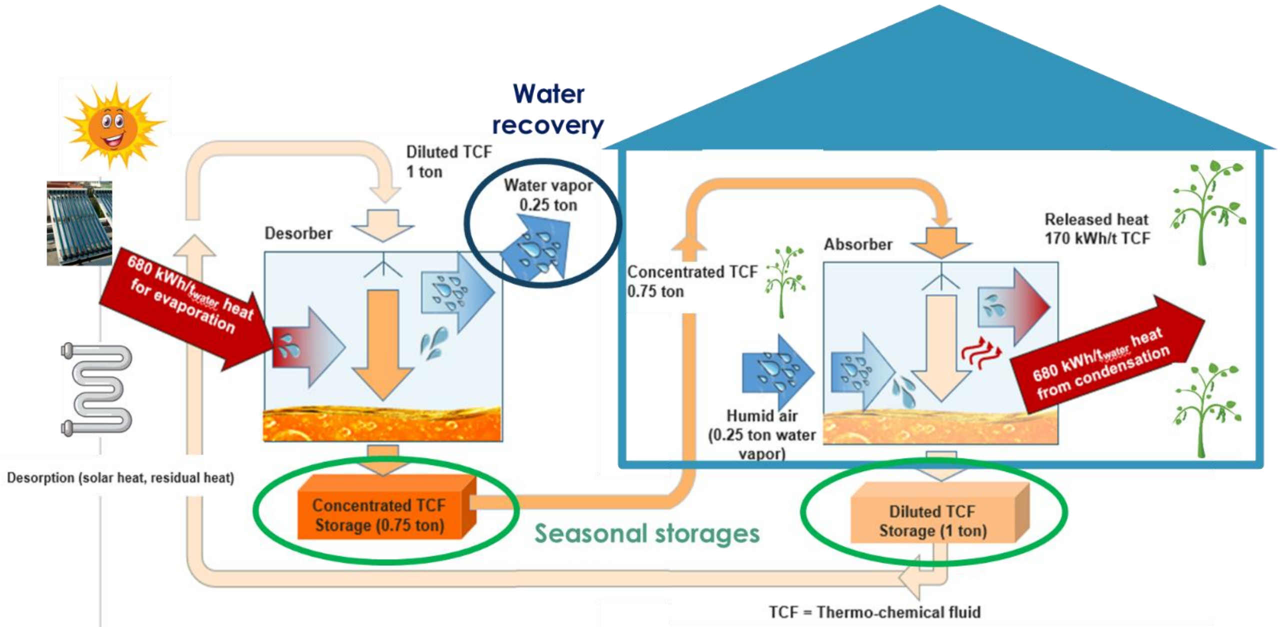


Figure 6. Fluid's loop for greenhouses.

TheGreefa is used in continental climate regions to regulate temperature and humidity inside greenhouses. The use of TheGreefa can reduce the energy required for heating, which in these regions significantly impacts the overall balance. By controlling humidity without opening windows and thus not releasing heat outside, the heat losses to the outside are reduced. Additionally, the absorption process releases further heat, further decreasing the energy required for heating. In Figure 7, on the left side, a traditional greenhouse is represented, and on the right TheGreefa greenhouse. The regeneration process takes place outside the greenhouse and the humid air Is then released to the atmosphere. In the continental region, there is no need to recover water.

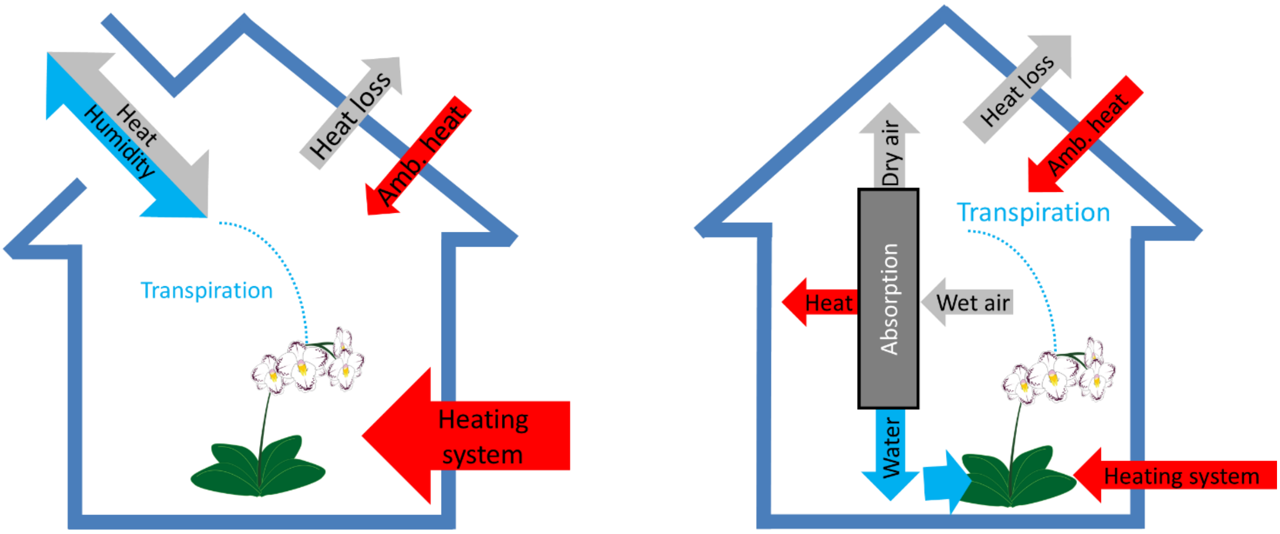


Figure 7. TheGreefa application compared to the standard greenhouse.

Absorber

The absorber is a very simple component, it is a plastic scrubber filled by random packing. Plastic is necessary because of the high level of corrosion of the TCF (salt solution).

The air flows from the bottom to the top, and the TCF from the top to the bottom. The packing increases the contact surface and contact time between the air and the TCF.

To ensure a high absorption grade, it is needed a minimum residence time of the two fluids inside the absorber. That is done by setting a maximum air velocity and a minimum the TCF flow density.

Figure 8. Packing.

In the Swiss demonstrator, the residence time is 1.5 seconds and two values are fixed 1 m/s for the air velocity (empty absorber) and 12 m3/(h m2) for the TCF flow density. This design parameter results in a diameter of 0.4 m and an active height of 1.3 m (active height is the part of the absorber, where there is contact between air and TCF).

The simple construction is shown in Figure 9: on the left, a transparent prototype is used in the ZHAW facility. The “white” part is filled by packing and it is the active height. On the right is the absorber installed in the Swiss demonstrator.

Figure 9. Transparent absorber at ZHAW-lab (left) and the absorber installed in the Swiss demonstrator (right).

Absorber: components

The absorber consists of different parts marked by different colours in Figure 10:

- Yellow: TCF distributor assures that the TCF is distributed homogenous in the entire section of the absorber;
- Blue: Active part / random packing: this part is filled with small random packings. Here the absorption process takes place;
- Red: the floating packing prevents aerosol formation in the scrubber;
- Purple: the sump collects the TCF coming from the active part and from here the TCF is pumped again to the absorber
- Green: the demister avoids that liquid drop leaving the absorber.

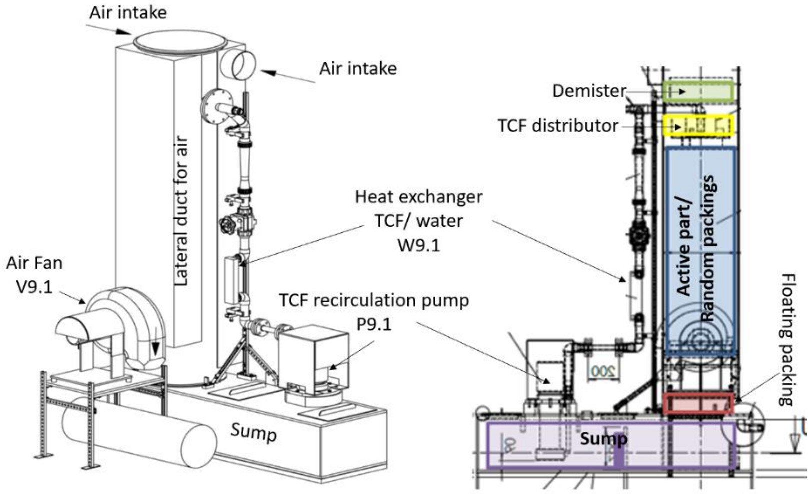


Figure 10. Absorber components.

The air is sucked into the absorber through a fan. The fan (V9.1) is located at the outlet air, the absorber operates under the ambient pressure. This solution avoids leakage of untreated air from the absorber.

On the TCF side, the TCF is extracted from the sump by the recirculation pump (submersible centrifugal pump-P9.1) and pumped via the plate heat exchanger (W9.1) into the absorber head, where it is evenly distributed over the packing by a liquid distributor.

The scrubber stands completely in the sump and has outlet openings for the salt solution at the bottom. This siphon separates the air in the scrubber from the atmosphere in the receiver tank so that it can be operated atmospherically open to the greenhouse environment. Between the scrubber and the solution circulation pump, there is an overflow in the storage tank which ensures a uniform flow and thus prevents the occurrence of a heterogeneous TCF concentration distribution.

All parts of the absorber in contact with the TCF are made of polypropylene or polyvinyl chloride. The heat exchanger has a coating of Parylene on the solution side.

Absorber: control of air temperature and humidity

The air humidity is controlled by the TCF concentration, while the air temperature is controlled by the TCF temperature.

The concentration of TCF inside the absorber shall be maintained at a certain percentage to allow the absorption process, only in this way it is possible to control the air humidity in the greenhouse. A too diluted TCF cannot any more control the air humidity.

The process for the humidity control is implemented as a batch process. As soon as the measurement point MR1 indicates a too high humidity, the TCF sump is drained and is filled up with concentrated TCF.

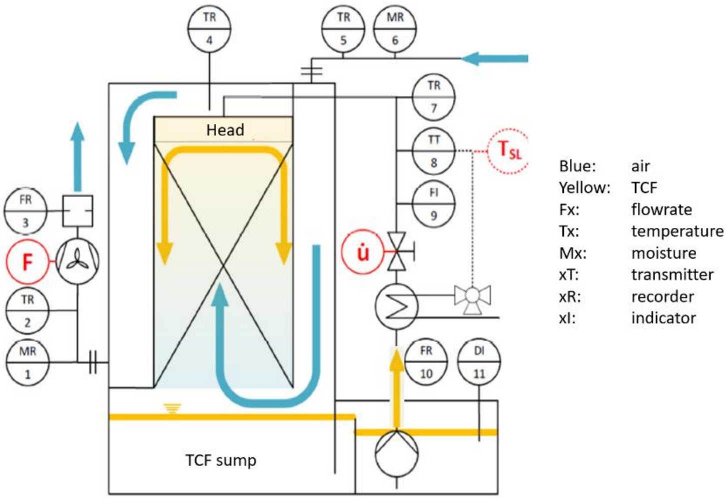


Figure 11. Absorber: control of air temperature and humidity.

The air temperature is measured at the absorber outlet (TR 2). If the temperature is outside the required range, e.g. too low or too high, the TCF is heated up or cooled down in the heat exchanger shown in Figure 11. In the Swiss greenhouse, the heat exchanger is a TCF/water heat exchanger.

Desorber: Regeneration

The desorber is used to regenerate (referred also as to concentrate) the diluted TCF.

The desorber has the same design as the absorber, but it is operated under positive pressure, the fan is at the air inlet. The air enters the desorber directly from the bottom and leaves it at the top.

The heat exchanger is used to give the energy input required for the desorption process.

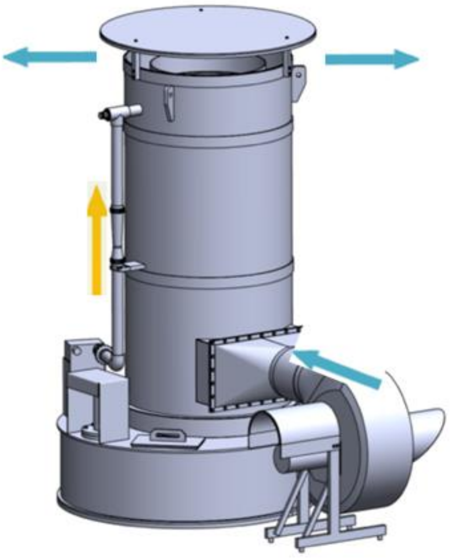


Figure 12. Desorber model.

The temperature in the desorber for the regeneration process (e.g. evaporation process of the water contained in the TCF and its absorption by the air) influences the velocity needed to reach the required concentration of the TCF.

The operation of the desorber is also a batch process. The desorber sump is normally empty. For the regeneration, it is filled up with diluted TCF which is recirculated from and back to the sump through the desorber. Based on the density measurement and the solution temperature the concentration of the TCF is determined. If the max TCF concentration is reached (in the Swiss demonstrator 32%), the desorption process is terminated and the concentrated TCF is pumped from the desorber sump into the concentrated TCF storage tank.

You can find more details on the webpage of Cordis or on webpage of TheGreefa under download/Publications, in the document ***Concept for a fully automated system and operating manual***.

Here the links:

Cordis: https://cordis.europa.eu/project/id/101000801/results/

TheGreefa: https://thegreefa.eu/wp-content/uploads/2024/06/THEGREEFA_D1.3-Control-system-and-operating-manual.pdf

2.1. Demonstration in Switzerland

The results presented here are for the Swiss demonstrator of TheGreefa project. The Swiss demonstrator is a greenhouse of 600 m^2, situated close to Zurich, in Switzerland. It is specifically designed for cultivating orchids. Rather than being placed directly on the floor, the crops are situated on tables, as shown in Figure 13.

Figure 13. Planting tables in the Swiss demonstrator. In green, the absorber is marked.

Energy balance in the Swiss demonstrator

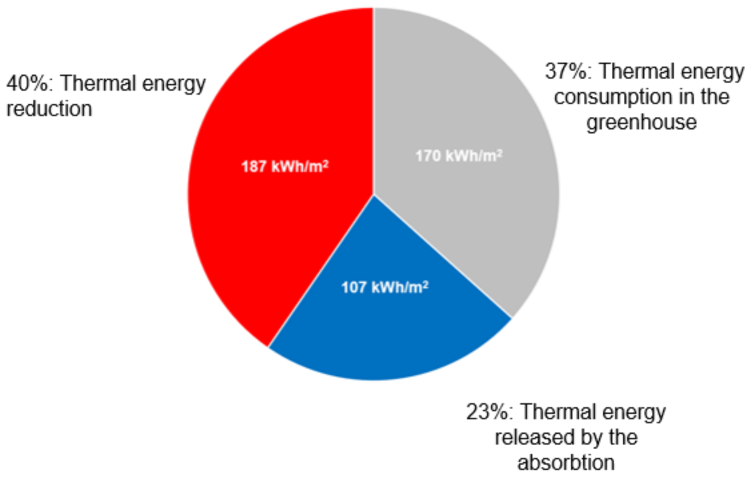


Figure 14. Annual thermal energy balance in the Swiss demonstrator.

Based on data measured over more than a year and their interpolation, the energy savings brought to the Swiss greenhouses by TheGreefa technology have been estimated. The 100% in the pie chart (Figure 14) represents the thermal energy that would have been required in the greenhouse without TheGreefa. 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. 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-temperature thermal energy, that would otherwise go unused.

The characteristic of TheGreefa is that the availability of this energy does not need to coincide with the use, in time and space. This energy can be stored for long periods without any energy loss in the form of concentrated TCF, retaining potential to release thermal energy rather than thermal energy. Finally, the grey segment is the thermal energy that must be supplied by the greenhouse operator.

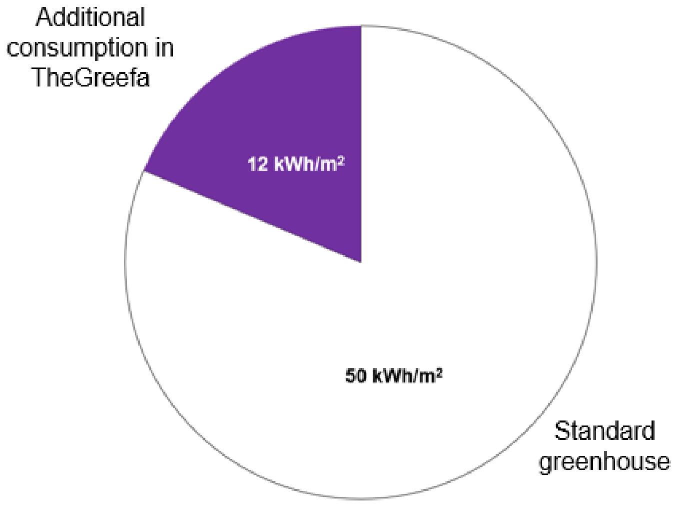


Figure 15. Annual electricity consumption in the Swiss demonstrator.

However, the situation is reversed when considering electricity consumption. As shown in Figure 15, with the installation of TheGreefa, electrical consumption increases by approximately 24%. It is important to consider that the rotating components, such as pumps and fans installed in TheGreefa system, have not been optimized for their electrical performance. Additionally, the design of air ducts and heat exchangers prioritized thermal performance, resulting in significant high-pressure losses. Therefore, there is potential to reduce this additional consumption through optimization efforts.

When considering the overall energy balance in the Swiss greenhouse, it is evident that electrical energy has a smaller impact compared to thermal energy. If we exclude the energy used for regeneration – whether because it is managed separately from the greenhouse operator or because remains otherwise unused – the total energy savings exceed 50%. Even when including the regeneration energy, substantial savings of around 35% are still achieved.

Table 1. Summary of the energy balance in the Swiss greenhouse.

	TheGreefa kWh/m² year	W/o TheGreefa kWh/m² year
Thermal energy	155	464
Electric energy	62	50
Total	**217**	**514**
Energy for regeneration (low temp. heat)	107	
Total incl. regeneration	**324**	**514**

TCF results

Based on the measured data of concentrated TCF used in the demonstrator (blue line in Figure 16), the production of concentrated TCF (green line in Figure 16) was simulated using heat source warm water generated in thermal solar panels located close to the greenhouse. For the Swiss greenhouse, approximately 100 m² of solar thermal panels are needed, which is about one-sixth of the greenhouse's surface area. Interestingly, the regeneration of TCF occurs year-round since it depends on the temperature difference between the air and the TCF, rather than on the absolute temperature. Production experiences a slight decrease during colder months due to shorter days and increased cloud cover.

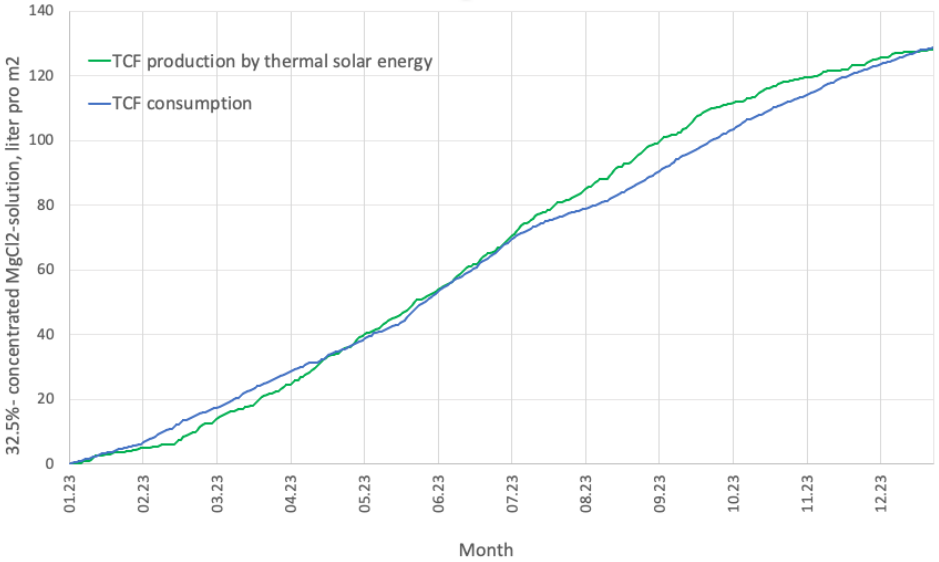


Figure 16. TCF ($MgCl_2$) absorption and regeneration.

Based on the quantity and usage pattern of TCF utilized and regenerated, the minimum required size for TCF storage has been determined (Figure 17). 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 and regeneration is slightly lower; by the end of this season (March) the storage is fully occupied by diluted TCF. Conversely, by the end of the warm season, due to opposite conditions, the storage is entirely filled by concentrated TCF. The required storage volume is approx. 175 litres per square meter of greenhouse area.

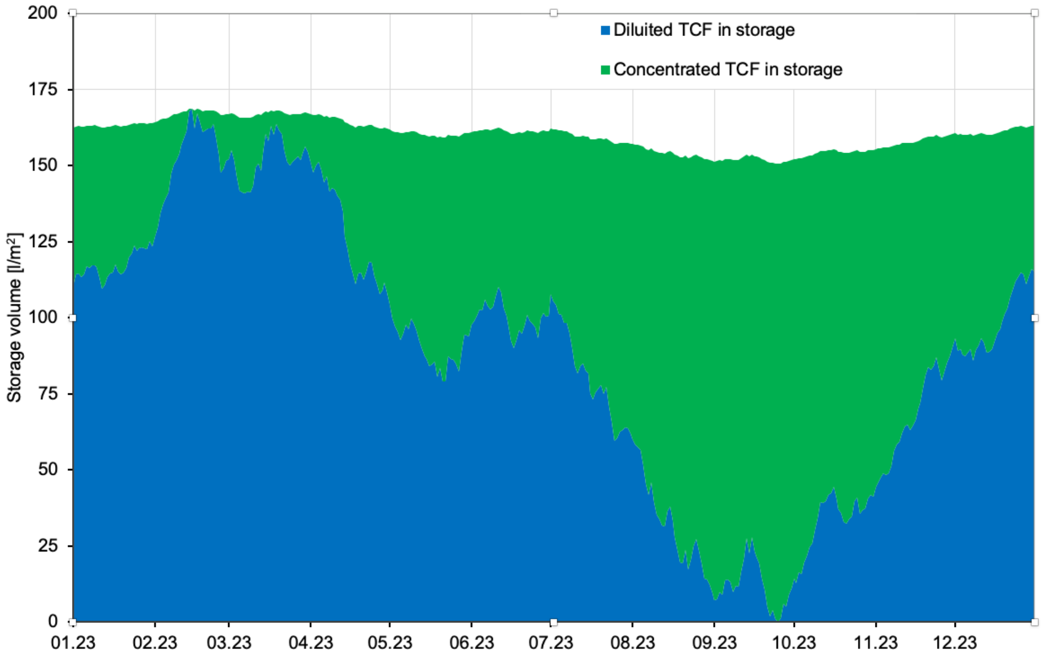


Figure 17. Storage volume.

Drying process

The drying process is very similar to the process for air humidity and temperature control. The difference is that in this case, the scope is to dehumidify the air, without temperature control

This application is explained in Figure 18. The air is dried in an absorber in counterflow with a concentrated TCF but is not necessarily heated, as heat could harm the leaves/vegetables and affect their quality. The configuration of the absorber can be the same as the absorber used in the greenhouse. In a closed cycle, the released dry air is then injected into the drying chamber where the humidity of the vegetables can be extracted.

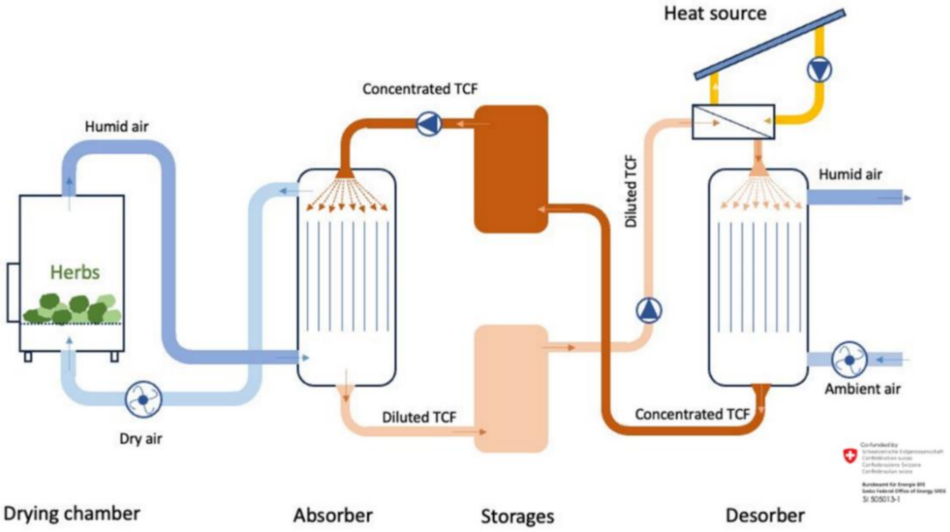


Figure 18. Drying process using the absorber and desorber.

The diluted TCF can then be stored without thermal loss and regenerated when renewable heat (e.g. solar heat) is again available. In comparison to state-of-art plants using compression dehumidifiers, in a sorptive dryer, the electrical energy consumption is limited to the operation of fans and liquid pumps, while the thermal energy required can be entirely provided by a low-temperature heat source, e.g. can be totally renewable. After the regeneration process, the energy provided can also be stored without any losses.

TCF selection

The choice of TCF to be used in the drying plant is different from that in the greenhouse.

Figure 20 shows the equilibrium line between different TCFs and humid air. The dashed lines represent air with varying humidity levels. The intersection points between the solubility lines of the TCFs and those of the air indicate the minimum humidity achievable at a given temperature. For example, at 20°C with an $MgCl_2$ solution, the maximum degree of dehumidification does not drop below 35%. $MgCl_2$ was chosen in the greenhouse for its availability and low cost, but its hygroscopicity is limited. At 20°C, the humidity of the air cannot be reduced below 35% RH. While for plant cultivation this humidity level is unacceptable because it is too low, for a drying process it is too high. An expensive alternative could be LiBr or LiCl solutions.

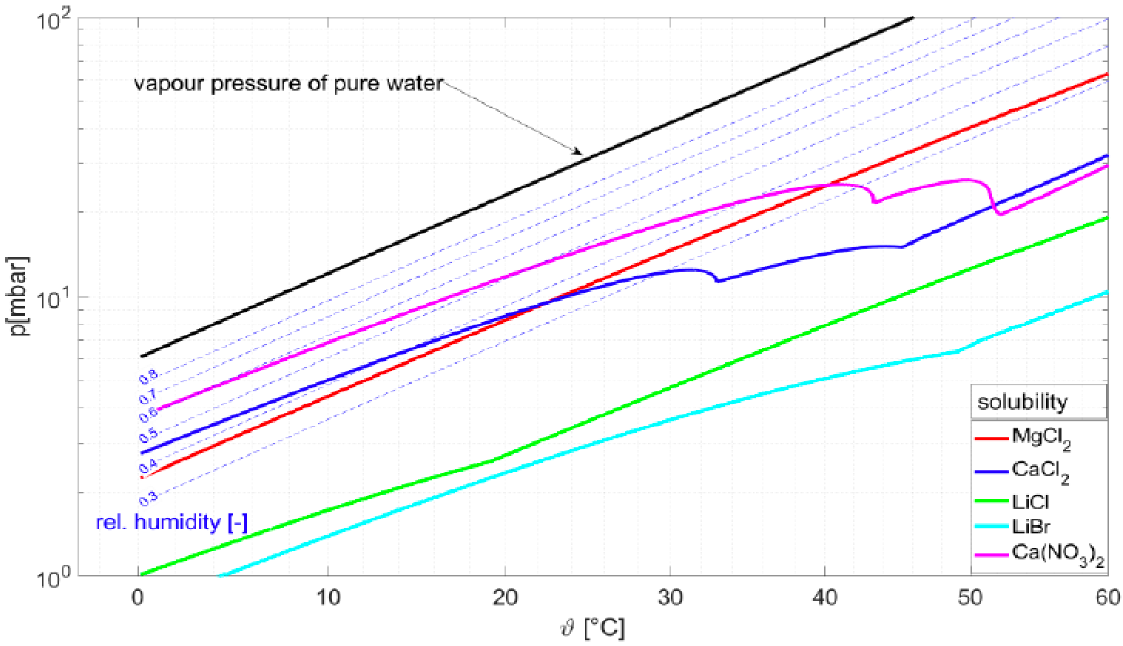


Figure 20. Comparison of different TCFs.

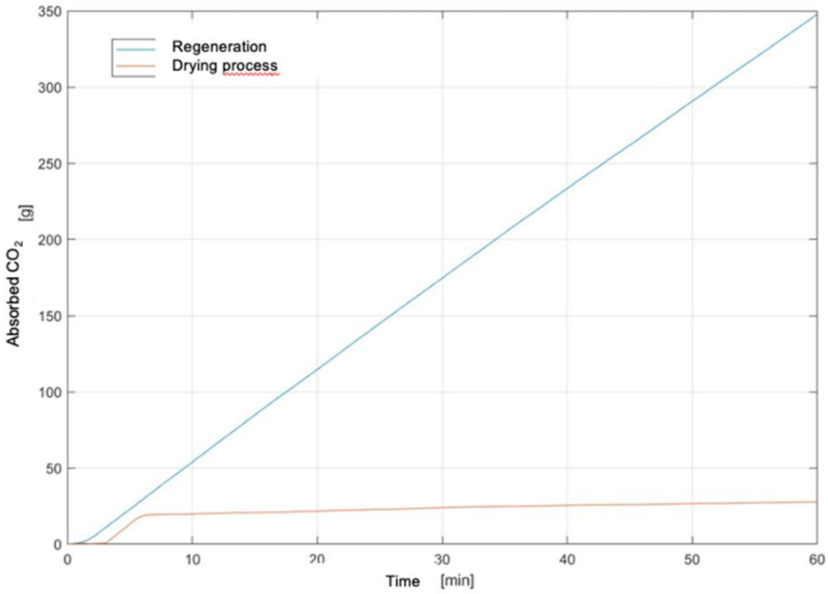
Figure 19. Dryer's interior with dried herbs.

Table 2. Different TCFs tested for the drying process.

Salt (TCF)	Chemical compounds	Air humidity at the equilibrium, 20°C
Caesium fluoride	CsF	3.38 %rH
Lithium bromide	LiBr	6.61 %rH
Zinc bromide	$ZnBr_2$	7.94 %rH
Sodium hydroxide	NaOH	8.91 %rH
Potassium hydroxide	KOH	9.32 %rH
Lithium chloride	LiCl	11.31 %rH
Calcium bromide	$CaBr_2$	16.50 %rH

For the drying process, we aimed to find and test a TCF with better hygroscopic properties than $MgCl_2$, but with affordable costs. Additionally, it needed to be a TCF compatible with the food industry. The characteristics of different TCFs were analysed in Table 2 and the choice was NaOH, which is widely used in baking and meets these requirements.

A problem that can arise with the use of NaOH is its reactivity with the CO_2 present in the air. This reaction forms carbonates that precipitate, so the precipitate must be removed and the reacted NaOH replenished. The issue can be minimized, if not eliminated, by recirculating the air in a closed loop. In Figure 21, CO_2 reacting with NaOH during the regeneration process is shown in blue. The regeneration was carried out at the ZHAW plant as an open cycle, where new ambient air was continuously supplied. In this case, continuous replenishment of NaOH is necessary.



Air flowrate: 500 Nm3/h

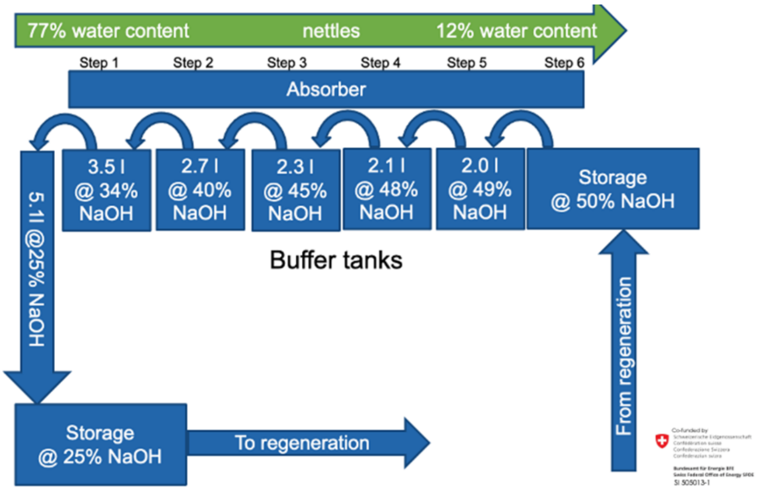
Drying process:
2.5 g CO_2 from 3 Nm^3 air -> 5 g NaOH

Desorption process:
Max 400g CO_2 g/hr -> 1.4% of treated NaOH /8 hr

Figure 21. CO_2 reaction with NaOH.

In the absorber for dehumidifying the air (drying process), the air is continuously recirculated. As shown by the red line, the CO_2 reacts with the NaOH only initially; once its level falls below the reaction threshold, it is no longer removed. NaOH does not require replenishment. The carbonates formed precipitate in NaOH solution and can be removed at the end of the drying cycle.

Process optimisation



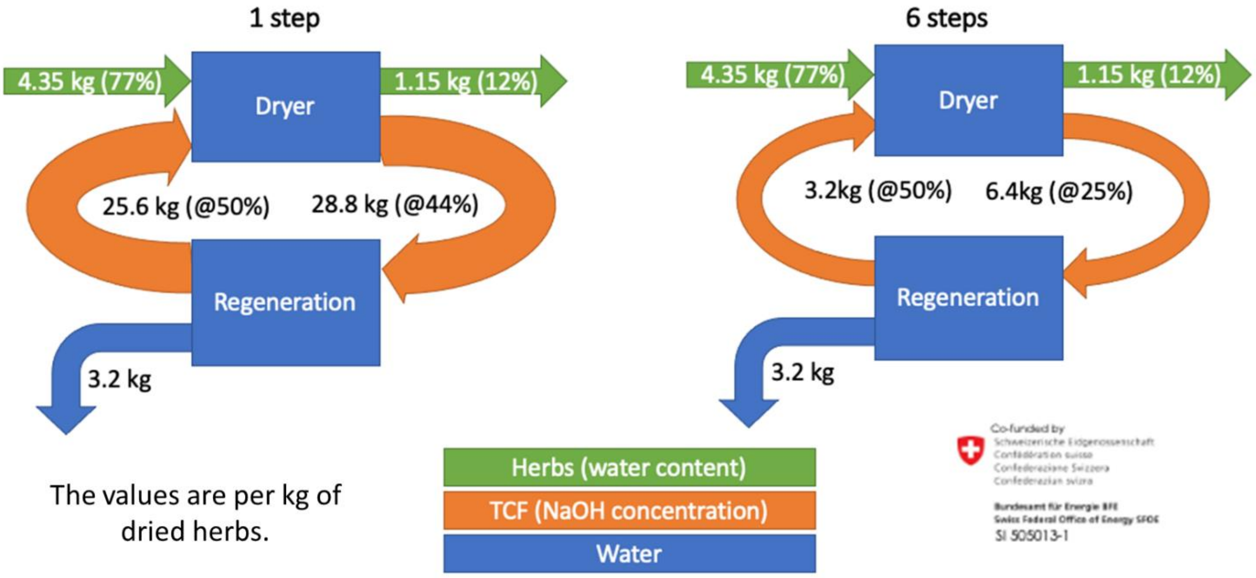
The values are per kg of dried herbs.

Figure 22. Proposed concept for the drying process.

The concentration of TCF used in the laboratory tests was 50% at the beginning of the drying process and 44% at the end. It was never replaced during the whole drying process.

The absorption power was therefore higher at the beginning than at the end. However, in the final stages, removing the remaining moisture from the nearly dried herbs is more challenging.

A high concentration of TCF is not strictly necessary at the beginning of the drying process, while it is essential in the final stages. For this reason, the concept illustrated in Figure 22 is proposed. process starts with a diluted TCF, which is then replaced in subsequent phases with increasingly concentrated TCF. This can be achieved by reusing the TCF from the final step of one batch of herbs in an earlier step of the next batch. Only when the TCF is so diluted that it can no longer absorb will it be sent for regeneration or to the diluted TCF storage.



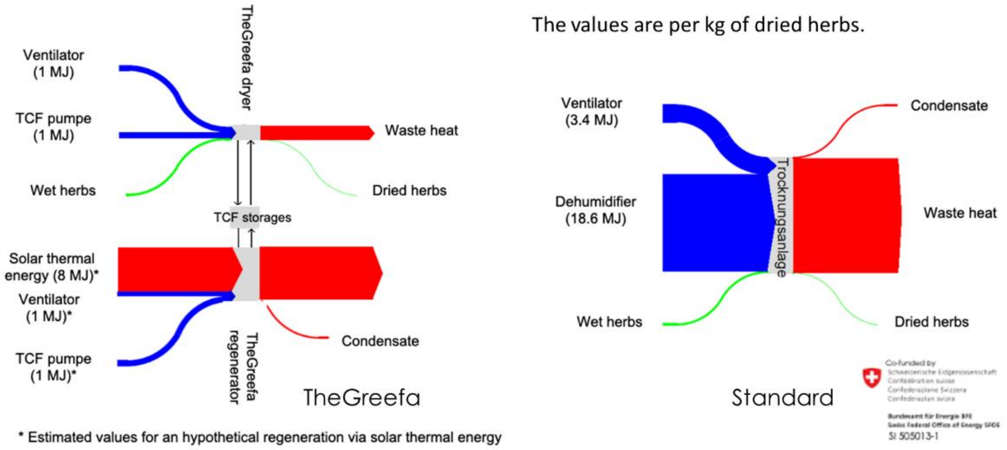
The values are per kg of dried herbs.

Figure 23. Volume reduction in the step process.

Using a step process, it is possible to reduce the volume required by the storage as illustrated in Figure 23. The energy required for the regeneration remains the same being the same as quantity of water to be evaporated.

Energy comparison

The specific energy consumption of a whole plant, including the regeneration of the TCF, has been estimated and compared with the real plant. In the picture of Figure 24, the blue arrows represent the electrical energy, and the red arrows the thermal energy.



The values are per kg of dried herbs.

* Estimated values for an hypothetical regeneration via solar thermal energy

Figure 24. Energy comparison between TheGreefa drying process and standard drying.

Considering that the regeneration will use thermal energy otherwise not used (let's say gratis energy), the specific energy demand of TheGreefa is clearly lower than that of conventional drying with a dehumidifier. It is important to emphasize that the great advantage of TheGreefa is not only that the process requires less energy than a conventional plant, but also that the thermal energy required is decoupled from the drying process.

This thermal energy can be entirely sourced from renewable energy or low-temperature waste heat that would otherwise go unused. Additionally, TCF can store thermal energy indirectly for a long time without any energy loss.

2.2. Demonstration in Tunisia

The main objective of this pilot project in the demonstration greenhouse in Tunisia is to assess the performance of a Brine-based Liquid Desiccant System (LDAS), used for greenhouse air conditioning. This investigation focuses on evaluating the efficiency of the LDAS in creating a balanced and controlled climate within the greenhouse under Tunisia's Climate Conditions. The LDAS system is implemented and tested in an innovative Water Cycling Greenhouse, which is characterized by an accordion shape designed to collect the maximum amount of condensate water.

In the system, the focus is put on the three points:

1. Desiccant regeneration during nighttime using heat stored during daytime:
    - Day/Night thermal heat accumulation and heat release (passive collection of cool from night).
    - Possibility of improved regeneration with additional heat source (plastic solar collectors, potentially residual heat from CSP).
    - Possibility of Regeneration using solar heater with 24 h operation.
2. Accumulation of CO_2 (1000 – 2000 ppm) in the closed atmosphere:
    - Improved photosynthesis if other growth factors like water/nutrients are also satisfied.
    - Improved production.
    - Improved heat acceptance allowing fewer cooling measures (sufficient CO_2 supply even at closed stomata resulting of heat- and/or water stress).
3. Water recovery by combined evapo-condensation:
    - Water from air humidity to desiccant during daytime,
    - Water from desiccant to air during nighttime,
    - Condensation of water at inner surface of the foil,
    - Removal of water droplets by modified roof shape, providing sufficient slope for droplet removal- and collection,
    - Heat removal by modified roof shape (zig-zag) for larger total surface of heat removal.

Components of the System of the Tunisian Demonstrator

The main components of the Pilot system in Tunisia are:

- The greenhouse with an accordion shape aiming to maximize condensate water collection,
- Two Absorber devices,
- The Desiccant loop (two storage tanks, pumps, pipes, electro-valves),
- The Air Loop (air ducts, fans),
- The Monitoring System.

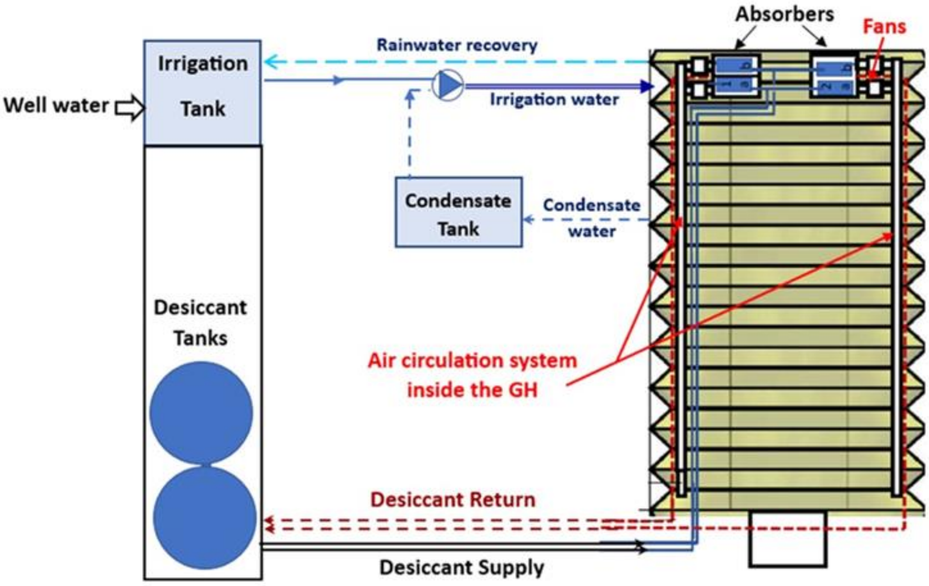


Figure 25. Scheme of the system.

The new design is aimed at receiving a much larger surface for heat rejection. At the same time, the collection of droplets is improved by the stronger slope of the foil, especially in the upper level of the tunnel.

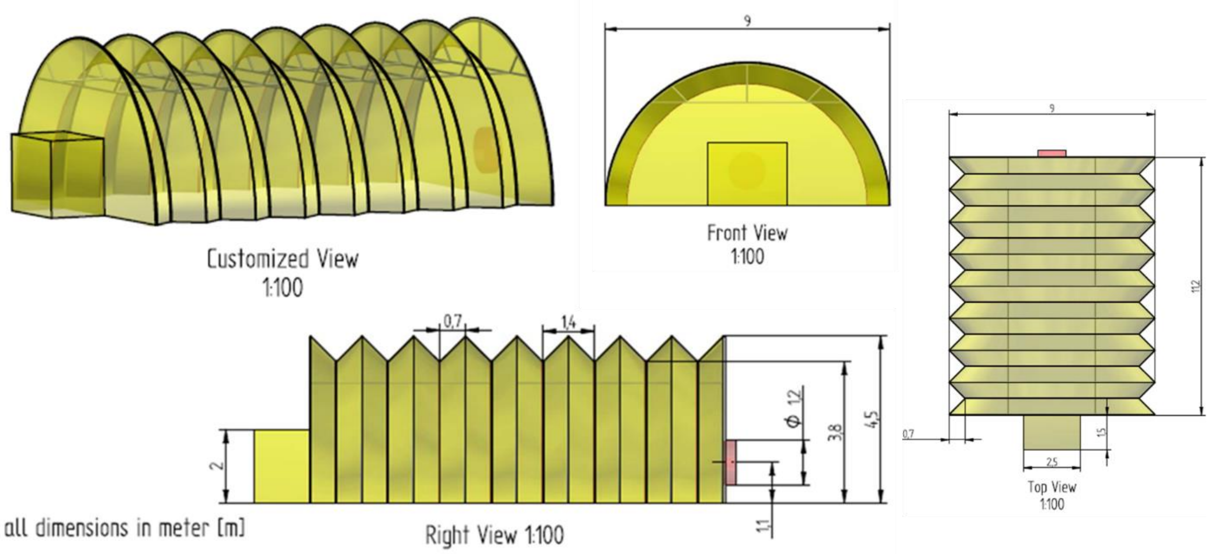


Figure 26. Greenhouse technical specifications – Zig-Zag (accordion) shape.

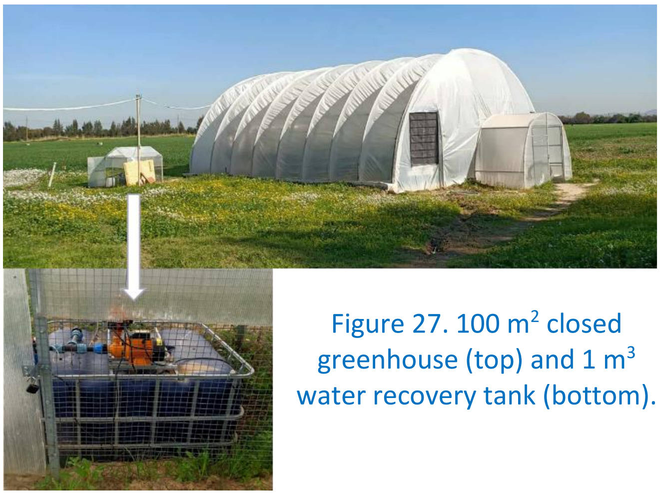


Figure 27. 100 m^2 closed greenhouse (top) and 1 m^3 water recovery tank (bottom).

The water tank presented in Figure 27 is a combined tank collecting rainwater from the rooftop of the greenhouse as well as collecting condensed water droplets from the inner surface of the greenhouse’s foil.

Absorber design

The absorber is the main component of the greenhouse air-conditioning system, ensuring the circulation in counterflow of the brine solution and the air drawn from the greenhouse.

This circulation allows the regulation of both air temperature and humidity by converting latent heat into sensible heat while absorbing air humidity.

The absorber was manufactured by the working group of the Technical University of Berlin (TUB) and Watergy GmbH.

Figure 28. The absorber installed in the Tunisian demonstrator (left) and inside structure of the absorber (right).

Initial tests of the absorber prototype provided clear information on deficits in liquid distribution. The infrared (IR) analysis (Figure 29) showed that heat release in the running process is unequal due to different flow rates in the centre (low flow) and perimeter (high flow).

By using a coloured liquid, also problems of unequal distribution were demonstrated. Deficits shown by the tests did result in a new design of absorbers. The unequal distribution of air in the bottom of the absorber was shown by fog analysis. The air was mainly led to the top from an area near the air entry, due to a dense configuration of absorber elements.

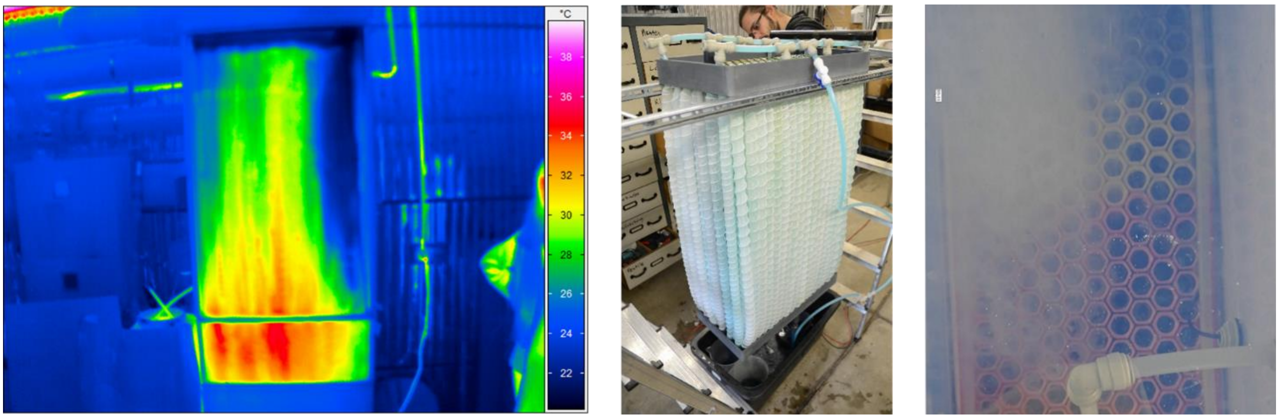


Figure 29. IR analysis (left), coloured liquid analysis (centre) and fog analysis (right).

A new design provided a shape of absorber elements with decreasing diameter towards the bottom, allowing air to enter the inner area of the volume.

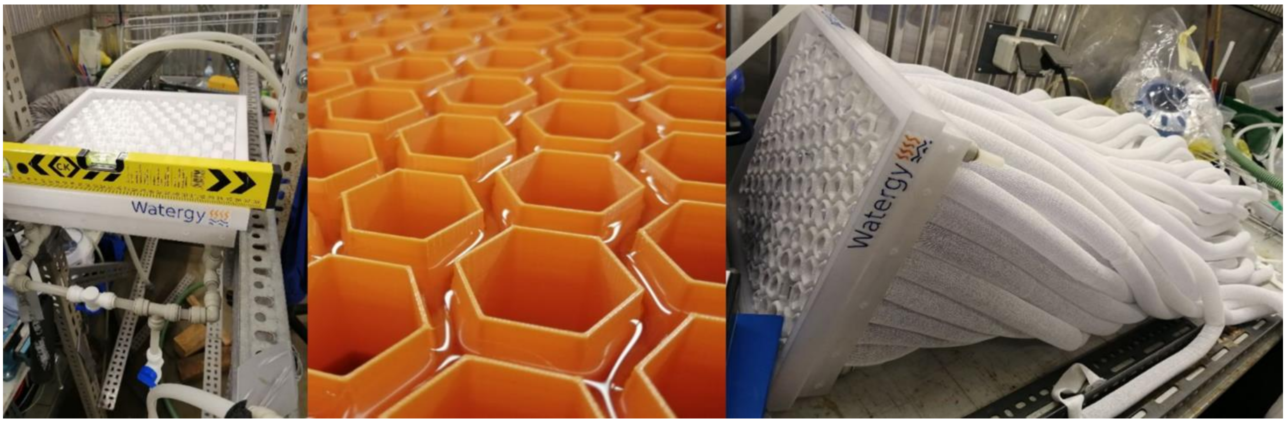


Figure 30. The absorber design with 3D printed hexagonal internal structure.

The new design for the absorber desiccant distribution element is aimed at a total decentralized supply of liquid between the hexagonal openings.

A central inlet is connected to a system of internal channels in the printed part, driving the fluid to plenty of openings.

The design is optimised for high volume flow (20l/min, withdrawal of ~5 kW of heat at ΔT=5K). The optimisation is performed for equalised flow of the solution.

Properties of the desiccant solution

Testing the performance of the desiccant:

- The effect of the Brine Solution provided by Sallina Sfax (Mare Alb) was tested under greenhouse climate conditions.
- Measurements have been performed for air inside a bottle of Brine solution and a bottle of water to compare the air temperature and humidity.

Figure 31. Measurement with 2 bottles.

Brine composition:

- Density: 1.350,
- Magnesium Mg: 112.65 g/l,
- Sulphate SO_4: 34.09 g/l,
- Other residues (Ca, Cl, K…): 428 g/l.

The operation of the absorber device of the system is based on the hygroscopic properties of the TCF used, which is a brine solution of magnesium chloride solution (MgCl2).

The measurements of the Equilibrium Relative Humidity (ERH) were performed during January 2022, according to the saturated salt solution method, which involves placing a sample of the brine solution in a sealed container and measuring the relative humidity of air in contact with the BLD. When air reaches equilibrium with the BLD, its relative humidity corresponds to the ERH of the desiccant fluid.

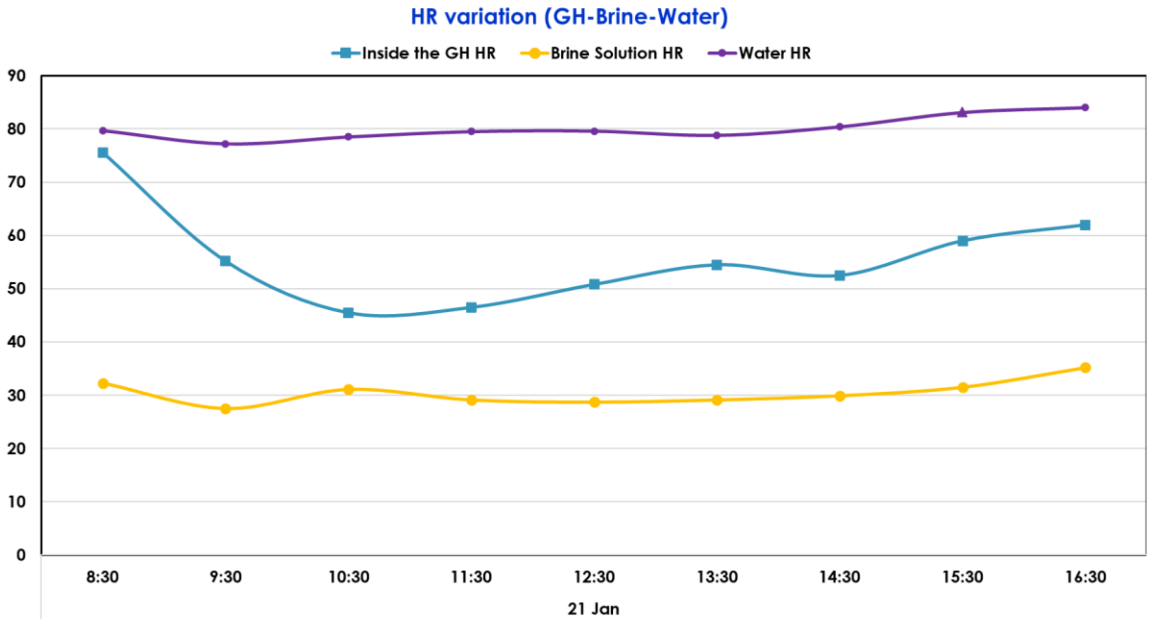


Figure 32. Brine solution effect - 21 January 2022.

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.

The yellow curve in Figure 32 shows the desiccant which is at low relative humidity. The purple curve shows relative humidity in the other container, containing just water. So, it can be seen it has very high relative humidity, as the air above the water is of course saturated. The blue line shows the relative humidity inside the greenhouse in the air which is surrounding these two containers.

Desiccant circulation in the system

Two interconnected storage tanks, with a total volume of 15 m^3 of the brine solution were utilized in the studied system. The storage tanks are connected to the absorber devices via two pumps and a hydraulic setup. The absorber devices were mounted on stands at a higher level than the storage tanks to allow the return of the TCF solution by gravity and reduce the complexity of the system's control.

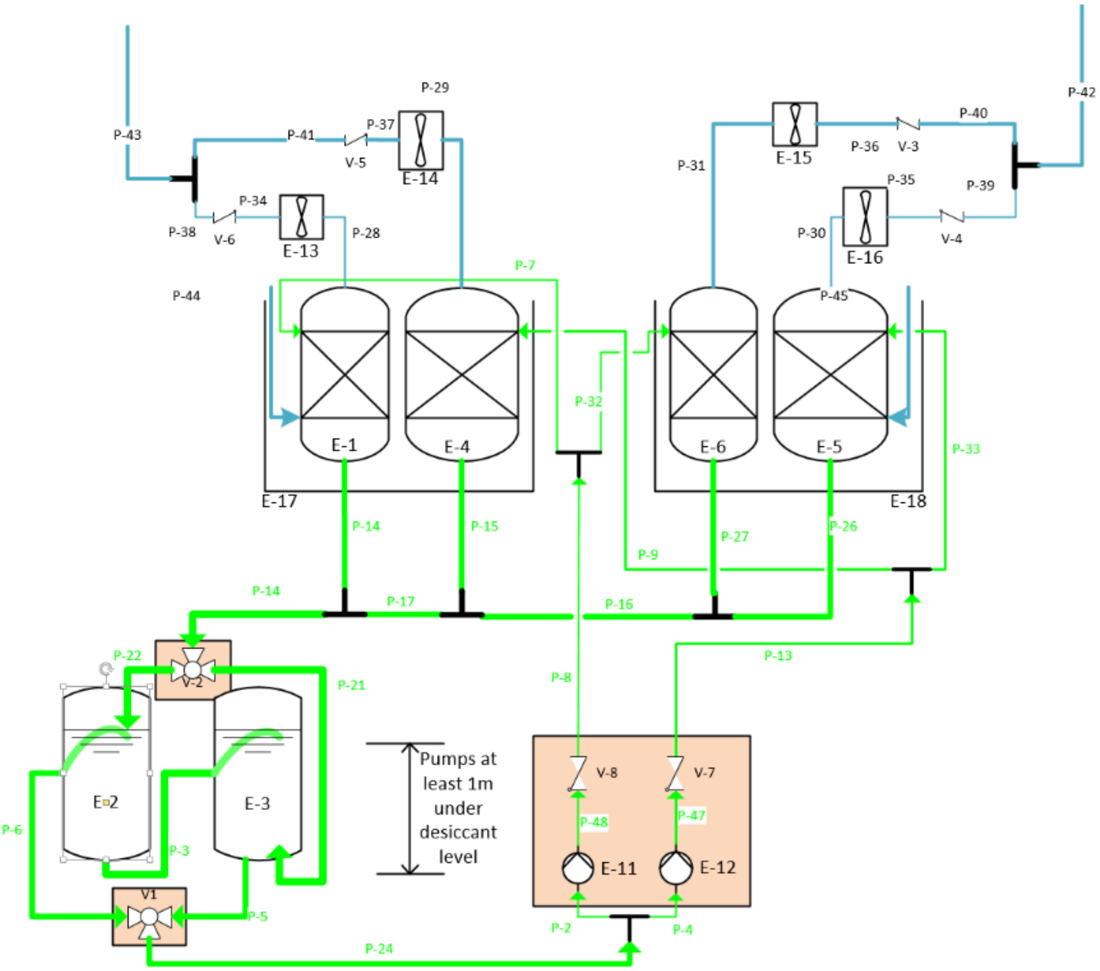


Figure 33. Installation of the Storage tanks and connection of the desiccant system components.

Figure 34. Pumps and electrovalves.

Air distribution inside the greenhouse

Air is drawn from the greenhouse roof and conveyed through the absorber. After undergoing thermal heat exchange and the dehumidification/humidification process, the processed air is blown into the greenhouse at the level of the plants.

Figure 35. Installation of the Absorber devices and the air circulation system inside the greenhouse (fans + air ducts).

Figure 35 presents the absorbers located in the rear of the greenhouse and the air distribution pipes at the sides (left photo). In the right photo the installed absorber is presented.

Monitoring system

The monitoring was implemented in the greenhouse to be able to monitor and control the system by the control computer. The control of the desiccant system operation is performed according to three stages in day and night modes. The 1st mode is run by only 1 pump. The 2nd mode is run by the second larger pump and in the 3rd mode where both pumps are running all together.

The implemented monitoring allows to perform measurements of:

- temperature and relative humidity,
- the desiccant flowrate,
- CO_2 concentration,
- the desiccant level inside the storage tanks.

Using the monitored data, it is possible to calculate the energy balance and the efficiency of the system.

Figure 36. Installation of the control box, the sensors and the data acquisition system.

Conclusions

As the last part of the presentation of the Tunisian demonstrator, some conclusions and learnings are presented below:

- High level of air tightness in the greenhouse is needed to reach condensation conditions.
- Error-friendly emergency ventilation is required but needs to support the concept of tightness.
- Installation of absorbers in the greenhouse (not outside).
- Absorber design successful in reduction of complexity and costs.
- 3D printed parts require high quality, heat resistant plastics and require sun shield.
- Storage volume is expensive and hydraulic connections are error prone.
- Desiccants need high attention concerning corrosivity, leakage, disposal and recycling.

The next steps that should be undertaken to improve the system and ensure higher efficiency and reliability are as follows:

- Use of phase-change material (PCM) for the heat storage will allow a reduction of desiccant quantity by 50-90%.
- Integration of PCM in absorber may also reduce pumping costs by 50-90% providing also slight reduction of ventilation requirements (~30%).
- Low cost PCM for melting point at around 30°C (Recycled chip fat or sodium carbonate can be consider for such use).
- Further simplification of Zig-Zag construction is possible, finally not much more expensive than existing tunnel greenhouses
- Further research activities required – also due to a lack of alternatives for overcoming the water crisis
- There are high recent activities in building air conditioning using liquid desiccants. Start-up companies such as "Blue Frontier" (funded by Bill Gates) and "7AC" are recent multi-million investments. There is high competition in this type of research, not only in the field of greenhouses.

3. Simulations and optimisation – Case studies

3.1. Case studies

The main objectives of the case studies are to analyse different boundary conditions in terms of two representative European climate regions selected in the project.

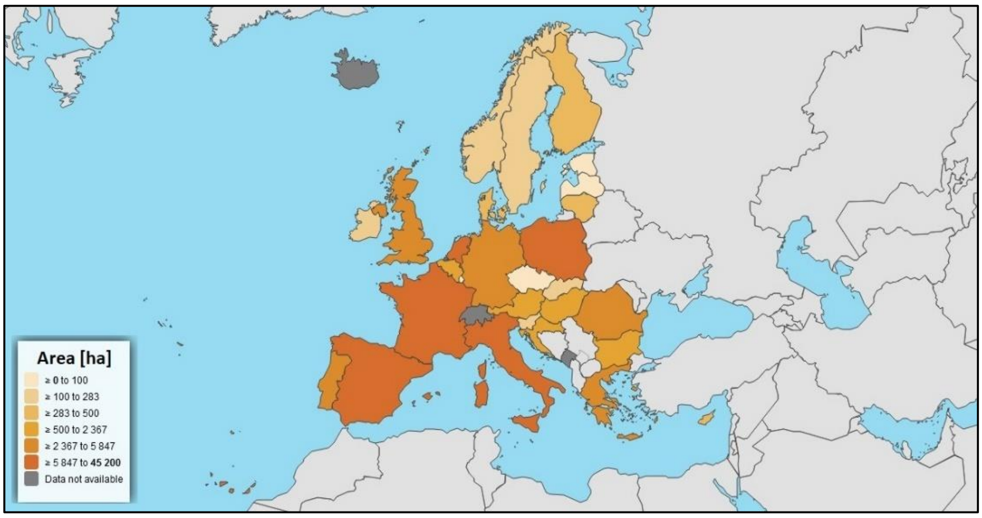


Figure 37. Greenhouse distribution in the countries of the European Union EU-27 (EUROSTAT, 2023a).

Spain, with the largest extension of horticultural greenhouses in Europe, was sleeted as the priority area of study. In 2023, the area of horticultural greenhouses was 77 923 ha.

Figure 38. Map of Spanish regions with different surfaces of greenhouses.

Italy, with a robust greenhouse industry, was identified in the previous Task T3.1 – Market evaluation as potential initial markets for TheGreefa. Here the greenhouses' area in 2023 was 35 229 ha.

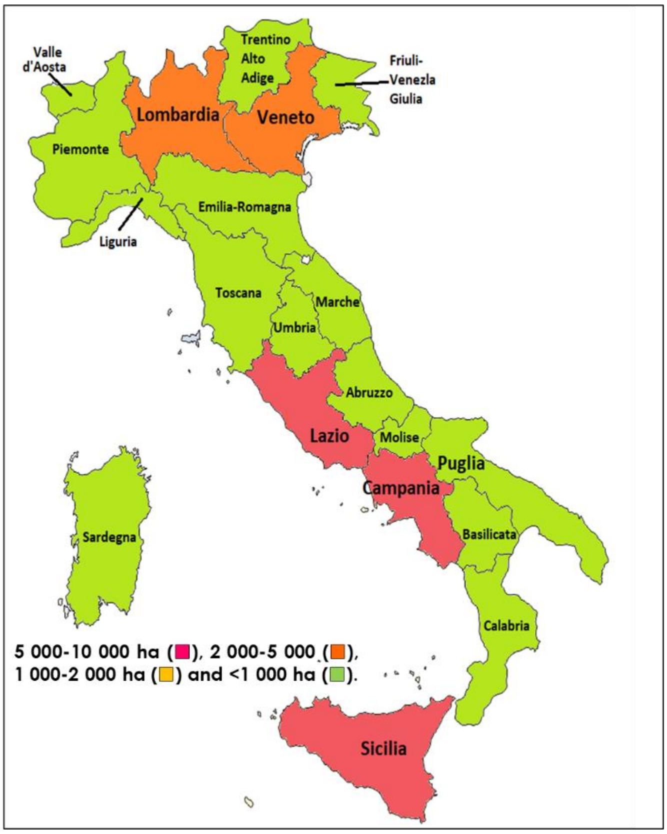


Figure 39. Map of Italian regions with different surfaces of greenhouses.

The scope of the analysis included three case studies which have been selected in Almería (Spain):

- Unheated Almería-type greenhouse naturally ventilated.
- Unheated multispan greenhouse with climate controller.
- Multispan greenhouses heated with natural gas.

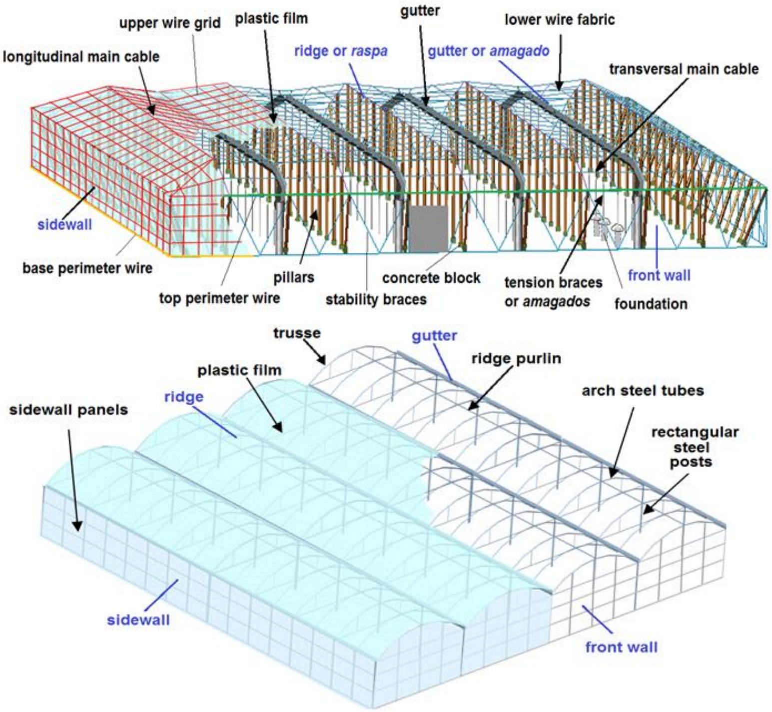


Figure 40. Simple greenhouse of Almeria-type with structure in "raspa y amagado“(top) and high-tech greenhouse with multispan structure (bottom).

In the Almería-type greenhouse of the University of Almería, two tomato crops developed in the 2017/18 season and in the current 2023/24 season have been analysed. Several alternatives of crop combinations have been grown in unheated multispan greenhouses during the development of TheGreefa project: cucumber-tomato, cucumber-pepper and tomato-zucchini.

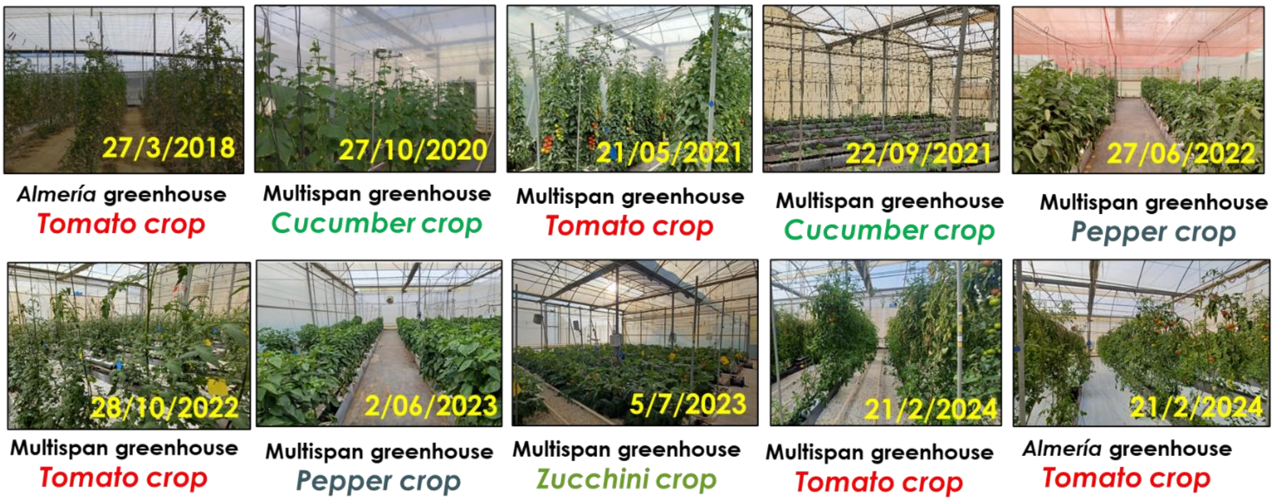


Figure 41. The most important crops that have been analysed in Almería and multispan greenhouses of the University of Almeria.

Two case studies have been selected in Italy for tomato production:

- Unheated multispan greenhouse.
- Multispan greenhouses heated with natural gas and oil and wood chips.

Figure 42. “Cherry” tomato crop in unheated multispan greenhouses (left) and heated multispan greenhouse (right).

Sources of information

- **The technical-productive characterization of the greenhouses of Almería** has been carried out through a survey carried out during the year **2022** by the **Andalusian Cooperative Society AFE** to 222 members, covering **610 greenhouses** (**1.4%** of the total area in Almería).
- **Production cost of greenhouses of Almería** for the seasons **2021-22** and **2022-23** have been analysed for **Almería-type unheated greenhouses** for seven different alternatives of crops cycles, from the data of the **Prices and Markets Observatory** of the Ministry of Agriculture, Livestock, Fisheries and Sustainable Development of the **Government of Andalusia - JA.**
- **Production costs, energy, water, fertiliser and phytosanitary products consumption** has been measured, during seasons **2020-21, 2021-22, 2022-23** and **2023-24** for **unheated**

Almería-type and **multispan greenhouses** of the **University of Almería** for **tomato, pepper** and **cucumber crops**.

- **Tomato production costs** of **unheated multispan greenhouses** in **Italy** have been obtained from governmental data (**Istituto di Servizi per il Mercato Agricolo Alimentare - ISMEA**) and **energy and water consumption** have been measured by **Sfera Agricola** in a commercial **heated multispan greenhouse**, estimating the associated production costs.
- A **Life Cycle Impact Assessment (LCIA)** has been developed estimating the main environmental impacts factors for the **five case studies** using the **EXCEL EUPHOROS environmental simulation model.**

In the case study, the main climatic parameters that affect the development of greenhouse horticultural crops have been analysed. The installation of the climate control system using thermochemical fluids can help maintain an adequate temperature and humidity, incorporate CO_2 from the outside environment and achieve greater homogeneity of these climatic parameters. The design of the air distribution system must prevent radiation loss at the crop level due to shading.

Analysed climate conditions for greenhouses cultivation:

- Adequate air, plant leaves and soil temperatures.
- Moderate relative humidity to avoid condensation or hydric stress.
    - Hight level of photosynthetically active radiation (PAR).
    - CO_2 concentration of air around the outside level of 420 ppm.
    - Uniformity of the different climate parameters.

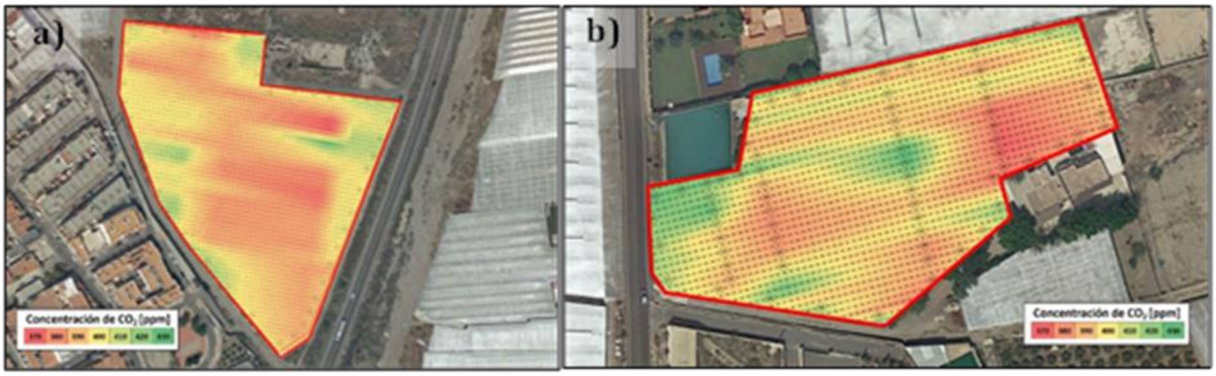


Figure 43. Distribution of CO_2 inside solar greenhouses of Almería of type "raspa y amagado" or simple (a) and "parral plano" or elemental (b).

Although there are multiple options for effective climate control in greenhouses, active systems require high energy use and passive systems are often limited by external weather conditions. The use of thermochemical fluids could be used as a complement to other systems in order to reduce energy use.

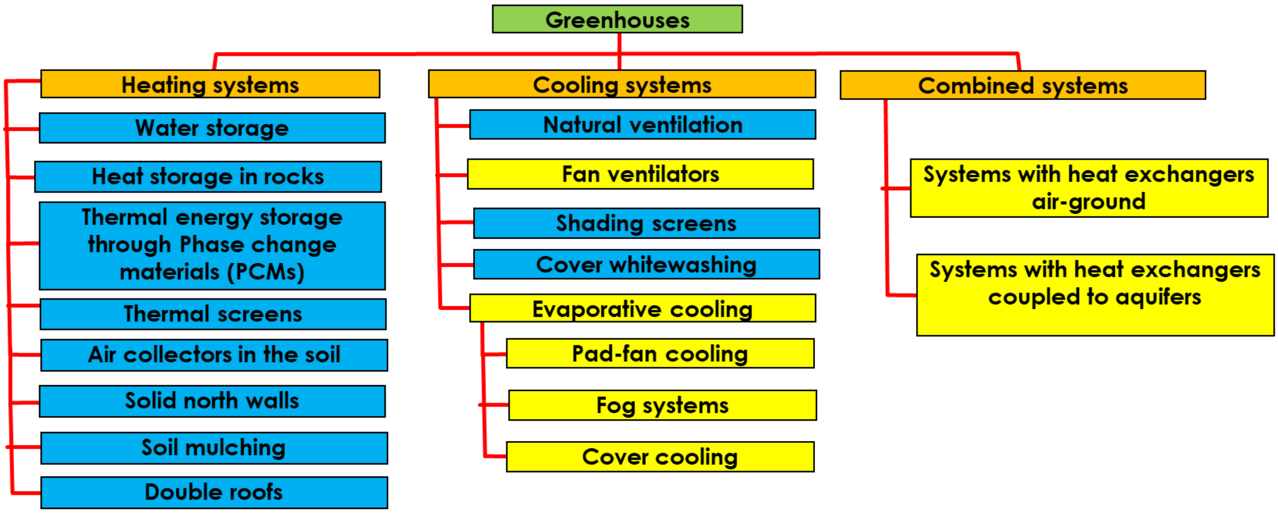


Figure 44. Classification of various climate control systems for greenhouses - passive methods (marked in blue).

Energy consumption in greenhouses is affected by the need for heating. In unheated greenhouses consumption varies from 30 to 100 GJ/ha, while in heated greenhouses the energy required can exceed 20 000 GJ/ha.

Table 3. Energy consumption of greenhouse agriculture in some European countries (several studies).

Country	Greenhouse area (ha)	Energy (GJ/ha)		Total energy		Gas emission	
		Heating	Electricity	(GJ/ha)	(kWh/m^2)	(toe/ha) [b]	(tCO$_2$eq/ha) [c]
Spain	77 923	81 – 16 272	2.8	84 – 17 784	2.3 – 158	2.0 – 332.0	13.6 – 1 277
Italy	35 229	11.8 – 9 450	13.5 – 65.6	62 - 14 616	1.7 - 406	3.0 - 349	11.6 – 1 344
Netherland	10 636	10 303 – 14 990	1 300	11 603 – 22 689	325 - 630	277 - 365	1 389 - 1 820
France	9 813	180 – 11 412	158 – 5 976	6 156 – 11 412	171 - 317	45 - 273	354 – 1 049
Greece	5 100	56 – 8 138	1.1	57 – 8 550	1.6 - 237	1.4 – 204	9 – 786
Germany	3 199	12 612 – 13 000	-	3 981– 16 308	111 - 453	302 - 390	1 163 – 1 499
Portugal	1 010	2 174 – 6 768	-	273 - 11 556	7.6	6.5	25
Total/Average	**120 930**	**39 020 571**	**3 871 189**	**1 562**	**155**	**1 717**	**48**

[a] 1 GWh = 8.60×10^{-5} Mtoe - Mega tonne oil equivalent (Krey *et al.*, 2014).
[b] Using a factor emission of CO$_2$ for heat production of 0.331 tCO$_2$eq/MWh (Krey *et al.*, 2014).

While in Spain the area of protected crops has increased up to 18.7% in the last seven years, in Italy the area occupied by greenhouses remains very stable.

Table 4. Area covered by greenhouses and vegetable production in the different regions of Spain and Italy.

Evolution of surface of greenhouses in different regions of Spain (MAPA, 2024).

Year	Andalucía	Murcia	Canary Islands	Spain
2016	48 509	6 235	6 744	65 674
2020	55 138	6 491	5 491	71 783
2023	61 099	6 449	5 495	77 923

+18.7%

Evolution of greenhouse surface in different regions of Italy (ISTAT, 2024).

Year	Lazio	Campania	Sicilia	Veneto	Lombardia	Italy
2016	7 845	10 332	7 676	3 360	2 076	35 574
2020	9 001	9 994	7 121	3 285	1 949	35 574
2023	7 629	7 523	7 029	3 748	3 642	35 229

–0.9%

The prices of horticultural products have significant variability depending on weather conditions in Europe or factors that affect marketing (COVID, Ukraine War). The highest prices were achieved in both Spain and Italy in 2023. In general, sales prices are between 15 and 20% higher in Italy.

Table 5. Average price [€/kg] obtained by farmers for greenhouse production in Spain and Italy in the last seasons (JA, 2024a; ISMEA, 2024a).

Country	🟥	🟨 **Spain**	🟨	🟥	🟩	**Italy**		🟥
Crops	**2016/17**	**2018/19**	**2020/21**	**2022/23**	**2017**	**2019**	**2021**	**2023**
Standard tomato	0.66	0.61	0.60	0.94	0.93	0.83	0.93	1.21
Cherry tomato	1.28	1.12	1.23	1.56	1.57	1.12	1.21	1.64
Pepper	0.91	0.77	0.84	1.23	0.74	0.88	1.00	1.51
Cucumber	0.70	0.53	0.57	0.95	0.42	0.48	0.54	0.74
Watermelon	0.35	0.30	0.31	0.40	0.21	0.34	0.25	0.48
Zucchini	0.68	0.54	0.50	0.67	0.93	0.97	1.12	1.16
Melon	0.41	0.48	0.40	0.49	0.52	0.65	0.61	1.05
Eggplant	0.73	0.60	0.55	0.74	0.63	0.71	0.86	1.02
Bean	1.69	1.83	1.63	2.26	1.84	1.63	2.90	0.80
Average	**0.63**	**0.65**	**0.63**	**0.90**	**0.76**	**0.78**	**0.86**	**1.05**

For each of the five selected case studies, production costs, water and energy consumption and their environmental impact have been analysed. The results obtained for each of the five cases analysed are presented below.

3.2. Case Study 1 – Unheated Almería-type greenhouse

The first case analysed is the Almería-type greenhouses, which account for more than 70% in Spain. Its investment cost is 15-20 €/m^2.

Figure 45. Almería-type greenhouse (a) and tomato crop inside (b) in the UAL-ANECOOP Experimental Station in Almería (Spain).

These greenhouses achieve productivity values normally lower than 15 kg/m^2, with production costs of 0.7 to 1.0 €/kg. Depending on the prices of each year, farmers can obtain a profit of up to 50,000 €/ha or obtain losses.

Table 6. Production costs measured for tomatoes grown in an Almería-type greenhouse in the seasons 2017/18 (costs updated to the 2022/23 season) and 2023/24, located in the Experimental Farm University of Almería-ANECOOP.

Greenhouse type		**Almería-type in "Raspa y amagado"**			
Farm area [m^2]	28 152	Greenhouse surface [m^2]		1 917	
Commercial type		On vine or branch		Tomato Pears	
Cycle length [days]		225		194	
Type of soil		Sand mulching		Coconut fiber substrate	
Average marketable yield Y_{CS} [kg/m^2]		**10.8**		**6.6**	
Type of cost		**€/ha**			
Supplies			24 823		19 127
Transport			2 181		1 153
Labour			30 675		24 206
Contracted external services			1 224		508
Total variable or direct costs, C_V [€/ha]			58 903		44 994
Investment cost [€/m^2]	Amortization [€/ha]	**17.8**	17 070	**18.4**	17 668
Total fixed or indirect costs C_F [€/ha]			17 743		20 995
Total cost [€/ha]			**76 645**		**65 990**
Unitary cost [€/kg]			0.71		1.00
Average price A_P [€/kg]			1.03		0.94
Total value crop [€/m^2]			11.12		6.21
Production value P_V [€/ha]			**111 240**		**62 111**
Annual operating income I_Y [€/ha]			34 595		-3 879

These greenhouses are those that require the least energy consumption, mainly in the irrigation system and the opening and closing of the windows (when they are motorized). Electrical energy consumption varies between 1 and 1.5 kWh/m^2, and water consumption varies between 15-75 l/m^2.

Table 7. Energy and water consumption measured in the experimental unheated Almería-type greenhouse of the University of Almeria.

Season	**2020-21**	**2021-22**	**2022-23**	**2023-24**
Crops	Cucumber+tomato	Cucumber+pepper	Tomato+zuchini	Tomato
Energy consumption				
Electicity price [€/kWh]	0.145	0.159	0.143	0.132
Electricity for ventilation [kWh/m^2]	0.398	0.379	0.452	0.230
Total electricity [kWh/m^2]	1.194	1.064	1.442	0.924
Electrical consumption [GJ/ha]	**43.0**	**38.3**	**51.9**	**33.3**
Water consumption				
Water consumption [m^3/ha]	2 185	5 242	4 854	2 945
Water price [€/m^3]	0.54	0.76	1.06	1.23
Water requirements [m^3/t]	**14.3**	**63.5**	**73.8**	**61.6**

In these greenhouses the lowest environmental impacts are achieved. The structure of the greenhouse and the irrigation system generate the greatest impact. The values calculated for the two tomato crops developed in the UAL greenhouses are similar to those published, with emissions between 95 and 280 kg CO_2 eq/tn.

Table 8. Total environmental impacts factors provided by the EXCEL EUPHOROS simulation model (Torrellas et al., 2013) for tomato crops in unheated Almería-type greenhouses of the University of Almería (UAL) and calculated by Martin-Gorriz et al., 2011 (MG) and by García Martínez, 2019 (GM) by functional unit (1 tonne of marketable tomatoes).

Crops	**UAL 2017-18**	**UAL 2023-24**	**MG 2011**	**GM 2019**
Yield [kg m^{-2}]	10.80	6.61	5.13	10.00
ADP - Abiotic depletion [kg Sb eq/tn]	1.66	2.00	0.01	0.79
AAP - Air acidification [kg SO_2 eq/tn]	1.05	1.20	1.75	0.68
EUP - Eutrophication [kg PO_4eq/tn]	0.35	0.42	2.70	0.25
GWP - Global warming [kg CO_2 eq/tn]	208.79	248.18	276.8	94.4
POP - Photochemical oxidation [kg C_2H_4/tn]	0.05	0.06	-	0.03
CED - Cummulative energy demand [MJ/tn]	4 346	5 210	2 242	1 725
Water consumption [m^3/tn]	30.17	33.86	38.00	44.80

3.3. Case Study 2 – Unheated multispan greenhouses in Spain

Unheated multispan greenhouses represent around 2% of the greenhouse area in Spain. The cost of this type of greenhouse varies from 25 to 38 €/m^2.

Figure 46. Unheated multispan greenhouse (a) and tomato crop inside (b) in the UAL-ANECOOP Experimental Station in Almería (Spain).

In these greenhouses, productions greater than 15 kg/m^2 can be achieved, depending on the combination of crops. Production costs vary from 0.5 to 1.5 €/kg, corresponding to 50-100 thousand €/ha. Higher investment costs make it difficult to obtain profits if products are sold at the average price. Normally, farmers with this type of greenhouses tend to obtain better sales prices through direct contracts with distribution companies.

Table 9. Production costs in the seasons 2020/21- 2023/24 of crops cultivated in the unheated multispan experimental greenhouses located in the Experimental Farm UAL-ANECOOP.

Season	**2020-21**	**2021-22**	**2022-23**	**2023-24**
Crops	Cucumber+tomato	Cucumber+pepper	Tomato+zuchini	Tomato
Greenhouse surface [m^2]	1 080	1 080	1 080	2 970
Days of crop	259	247	294	174
Marketable yield, Y_C [kg/m^2]	**15.3**	**8.25**	**6.58**	**4.78**
Supplies	26 791	24 323	36 802	17 163
Transport	5 096	3 654	8 303	2 307
Labour	27 161	26 232	34 147	18 141
External services	1 640	147	677	508
Total variable or direct costs, C_V [€/ha]	60 688	54 357	79 929	38 119
Total investement cost, C_I [€/m^2]	**34.0**	**35.8**	**37.6**	**22.9**
Amortization costs, $C_A=C_I/N_Y$ [€/ha]	19 374	20 558	21 566	13 172
Total fixed or indirect costs, C_F [€/ha]	20 014	22 018	22 699	15 816
Total cost, T_C [€/ha]	**80 702**	**76 375**	**102 628**	**53 936**
Unitary cost, $U_C=T_C/Y_C$ [€/kg]	0.53	0.93	1.56	1.13
Average price, A_P [€/kg]	0.58	0.81	1.35	1.14
Total value crop, $P_V=A_P \cdot Y_C$ [€/m^2]	8.89	6.68	8.87	5.45
Revenue of production, $P_V=A_P \cdot Y_C$ [€/ha]	**88 896**	**66 752**	**88 733**	**54 492**
Annual operating income, $I_Y=P_V-T_C$ [€/ha]	8 194	-9 623	-13 895	556

Electrical energy consumption is similar to the Almería type, variating between 1 and 1.5 kWh/m^2, and with water consumption varying between 15 and 75 l/m^2.

Table 10. Energy and water consumption measured in experimental unheated multispan greenhouses of the University of Almeria.

Crops	Tomato 2022-23	Tomato 2023-24
Energy consumption		
Electicity price [€/kWh]	0.143	0.132
Ventilation electrical consumption [kWh/m²]	0.350	0.411
Total electrical consumption [kWh/m²]	1.576	1.053
Electrical consumption [GJ/ha]	**56.7**	**37.9**
Water consumption		
Water consumption [m³/ha]	3 258	2 238
Water price [€/m³]	1.06	1.23
Water requirements [m³/t]	**30.2**	**33.9**

As for Almería type, the structure of the greenhouse and the irrigation system generate the greatest impact. As consequence of the greater use of metal in the construction of the greenhouse, the impacts are generally higher than those of the first case, with emissions between 150 and 1000 kg CO_2 eq/tn.

Table 11. Total environmental impacts factors provided by the EXCEL EUPHOROS simulation model (Torrellas et al., 2013) for tomato crops in unheated multispan greenhouses of the University of Almería (UAL) and calculated by Martínez-Blanco et al., 2011 (MB) and by Torrellas et al., 2012 (TR) by functional unit (1 tonne of marketable tomatoes).

Crops	UAL 2020-21	UAL 2022-23	UAL 2023-24	MB 2011	TR 2012
Yield [kg m⁻²]	6.19	5.73	4.78	15.90	16.50
ADP - Abiotic depletion [kg Sb eq/tn]	7.92	7.60	6.63	1.06	1.26
AAP - Air acidification [kg SO_2 eq/tn]	6.54	5.95	5.31	0.94	0.92
EUP - Eutrophication [kg PO_4eq/tn]	3.71	3.40	3.01	0.35	0.50
GWP - Global warming [kg CO_2 eq/tn]	998.88	979.70	851.55	153.0	197.8
POP - Photochemical oxidation [kg C_2H_4/tn]	0.41	0.35	0.31	0.03	0.03
CED - Cummulative energy demand [MJ/tn]	19 678	18 888	16 560	2 554	3 067
Water consumption [m³/tn]	16.85	64.28	61.61	39.11	28.78

3.4. Case Study 3 – Heated multispan greenhouses in Spain

The last case selected to characterize Spanish greenhouses are the heated multispan, that represent less than 2% of the greenhouses of Spain. The cost of this type of greenhouse varies between 45-58 €/m².

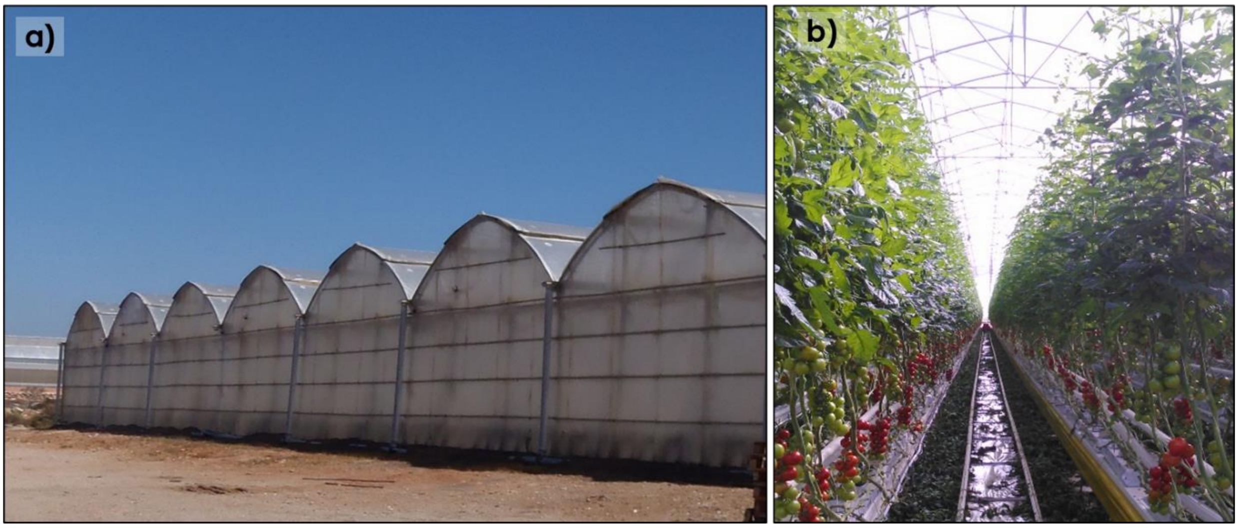


Figure 47. Heated multispan commercial greenhouse with double cover (a) and tomato crop inside (b) of the company Natural Growers in Almería.

The use of heating allows increasing productivity above 20 kg/m^2. The highest production cost is natural gas for heating, around 40%. Depending on the prices of fuel and vegetables, farmers can earn or lose money. As in the previous case, if the average sales price is considered, it is normal to obtain losses. Farmers generally sign contracts directly with supermarket chains to ensure a profit.

Table 12. Production costs updated to the 2022/23 season of crops cultivated in 2013/14 in three heated multispan greenhouses of the company Natural Growers in Almería.

Greenhouse type	**Plastic multispan with inflated double cover**		
Farm area [m^2]	158 140		
Greenhouse surface [m^2]	35 200	11 600	7 200
Crops	Cucumber	Tomato "Cherry"	Tomato "Branch"
Cycle length [days]	280	308	308
Average marketable yield Y_{CS} [kg/m^2]	**20.98**	**8.21**	**19.79**
Type of cost Subtype of cost	€/ha		
Supplies	107 762	110 164	111 041
Energy for heating	72 792	72 792	72 792
Transport	2 713	1 781	3 896
Labour	39 829	45 168	45 814
External services	1 147	520	1 722
Total variable or direct costs C_V [€/ha]	151 451	157 633	162 473
Investment cost [€/m^2]	**52.8**	Amortization [€/ha]	27 646
Total fixed or indirect costs C_F [€/ha]	31 210	31 768	30 480
Total cost, T_C [€/ha]	**182 661**	**189 401**	**192 953**
Unitary cost, $U_C=T_C/Y_C$ [€/kg]	0.87	2.31	0.98
Average price, A_P [€/kg]	0.88	1.66	0.97
Total value crop, $P_V=A_P \cdot Y_C$ [€/m^2]	18.40	13.63	19.16
Revenue of production, $P_V=A_P \cdot Y_C$ [€/ha]	**184 048**	**136 341**	**191 648**
Annual operating income, $I_Y=P_V-T_C$ [€/ha]	1 387	-53 059	-1 305

The use of heating increases energy consumption above 120 kWh/m^2. Water consumption can also increase due to the greater transpiration of the crop, with values of 60-150 l/kg.

Table 13. Energy and water consumption measured in three heated multispan greenhouses of the company Natural Growers in Almería with prices updated to the 2022/23 season.

Crop	**Cucumber**	**Tomato "Cherry"**	**Tomato "Branch"**
Energy consumption			
Electicity price [€/kWh]	0.143	0.143	0.143
Consumption in ventilation [kWh/m^2]	0.242	0.242	0.242
Total electrical consumption [kWh/m^2]	2.800	2.800	2.800
Electrical consumption [GJ/ha]	**100.8**	**100.8**	**100.8**
Natural gas price [€/m^3]	0.607	0.607	0.607
Natural gas consumption [m^3/m^2]	11.99	11.99	11.99
Heating energy consumption [kWh/m^2]	128.7	128.7	128.7
Heating energy consumption [GJ/ha]	**4632**	**4632**	**4632**
Water compsuption			
Water consumption [m^3/ha]	19 198	11 982	11 982
Water price [€/m^3]	0.75	0.75	0.75
Water requirements [L/kg] or [m^3/t]	**91.5**	**145.9**	**60.5**

The use of heating also significantly increases emissions to values of 900-3500 kg CO2 eq/tn.

Table 14. Total environmental impacts factors provided by the EXCEL EUPHOROS environmental simulation model (Torrellas et al., 2013) for the crops grown in three heated multispan greenhouses of the company Natural Growers (NG) in Almería with organic production (without use of insecticides or fungicides) and calculated by Pérez Neira et al., 2018 (PN) for tomato crops by functional unit (1 tonne of marketable tomatoes).

Crops	Cucumber	T. Cherry	T. Branch	PN 2018
Yield [kg m^{-2}]	20.98	8.21	19.79	15.30
ADP - Abiotic depletion [kg Sb eq/tn]	11.83	30.35	12.59	-
AAP - Air acidification [kg SO_2 eq/tn]	1.45	3.78	1.57	-
EUP - Eutrophication [kg PO_4eq/tn]	0.17	0.90	0.23	-
GWP - Global warming [kg CO_2 eq/tn]	1 389.7	3 568.9	1 481.2	920.0
POP - Photochemical oxidation [kg C_2H_4/tn]	0.11	0.28	0.11	-
CED - Cummulative energy demand [MJ/tn]	24 927	63 967	26 544	13 140
Water consumption [m^3/tn]	91.51	145.94	60.55	-

3.5. Case Study 4 – Unheated multispan greenhouse in Italy

The first case selected in Italy is multispan greenhouses without heating. Its cost varies between 20-80 €/m^2.

Figure 48. Unheated multispan commercial greenhouse (a) and tomato crop inside (b) in Italy (COSER. 2024; De Marinis, 2023).

In these greenhouses, production is not very high, so many farmers opt for high-value crops such as Cherry tomatoes. As in the case of Spain, the high investment requires farmers to ensure sales prices higher than average to avoid incurring losses.

Table 15. Production costs estimated for tomato "Cherry" cultivated in commercial unheated multispan greenhouses in Italy in the season 2022/23 (ISMEA, 2024 a-c).

Greenhouse type	**Multispan**		
Farm area [m^2]	100 000	Greenhouse surface [m^2]	10 000
Farm type	Average of commercial	Location	Ragusa (Italy)
Crop specifications			
Commercial type	Cherry	Crop type	Grafted
Cycle	6 months	Cycle length	180 days
Average marketable yield Y_{CS} [kg/m^2]			**5.55**
Type of cost			**€/ha**
Total variable or direct costs, C_V [€/ha]			40 550
Investment cost [€/m^2]	Amortization [€/ha]	**25.5**	22 462
Total fixed or indirect costs C_F [€/ha]			10 303
Total cost [€/ha]			**108 331**
Unitary cost [€/kg]			1.96
Average price A_P [€/kg]			1.60
Total value crop [€/m^2]			8.83
Production value P_V [€/ha]			**88 331**
Annual operating income I_Y [€/ha]			-20 000

Energy and water consumption are similar to those of unheated multispan greenhouses in Spain. However, the cost of water of approximately 0.25 €/m^3 is much lower than in Almería (0.75-1.25 €/m^3).

Table 16. Energy and water consumption estimated for commercial unheated multispan greenhouses in Italy for the season 2022/23.

Energy consumption		**Source**
Electicity price [€/kWh]	0.210	ARERA (2023)
Total electrical consumption [kWh/m^2]	1.9	Estimated from ISMEA (2024 a)
Electrical consumption [GJ/ha]	**67**	Calculated
Water consumption		
Water consumption [m^3/ha]	4 570	Bacci et al. (2005)
Water price [€/m^3]	0.25	CBTC, 2024
Water requirements [m^3/t]	**82.7**	Calculated

The metal structure of multispan greenhouses generate emissions between 750-1200 kg CO_2 eq/tn.

Table 17. Total environmental impacts factors provided by the EXCEL EUPHOROS environmental simulation model (Torrellas et al., 2013) for tomato "Cherry" grown in unheated multispan greenhouses in Italy and calculated by Cellura et al., 2012 (CL) by functional unit (1 tonne of marketable tomatoes).

Crops	**Tomato "Cherry" 2022-23**	**CL - Tomato**	**CL – Tomato "Cherry"**
Yield [kg m^{-2}]	5.53	-	-
ADP - Abiotic depletion [kg Sb eq/tn]	5.73	-	-
AAP - Air acidification [kg SO_2 eq/tn]	4.71	5.70	9.80
EUP - Eutrophication [kg PO_4eq/tn]	3.52	2.10	3.70
GWP - Global warming [kg CO_2 eq/tn]	868.8	740.0	1 245.9
POP - Photochemical oxidation [kg C_2H_4/tn]	0.21	0.30	0.50
CED - Cumulative energy demand [MJ/tn]	14 141	16 200	23 000
Water consumption [m^3/tn]	82.64	88.90	77.70

3.6. Case Study 5 – Heated multispan high-tech greenhouses in Italy

The last case selected corresponds to heated greenhouses in Italy with a high level of technology in climate control systems. The cost of these greenhouses is the highest with values of 70-160 €/m^2.

Figure 49. Heated multispan commercial greenhouse (a) and tomato crop in substrate with heating pipes (b) of Sfera Agricola in Italy.

In these greenhouses the cost of energy for heating represents between 20 and 40% of the total costs. Heating allows increase production above 50 kg/m^2. The economic risk is greatly increased, so both profits and losses can be much greater than in unheated greenhouses.

Table 18. Estimation of production costs of tomato "Cherry" cultivated in commercial high-tech multispan greenhouses in Italy heated with natural gas in the seasons 2013/14 (costs from Battistel, 2014 updated to the 2022/23 season) and heated with diesel and wood pellets in the seasons 2022/23 (energy measured by Sfera Agricola).

Greenhouse type		**Heated multispan high-tech**	
Greenhouse surface [m^2]		50 000	119 232
Cycle length [days]		320	343
Average marketable yield Y_{CS} [kg/m^2]		**50.0**	**15.0**
Type of cost		**€/ha**	
Supplies		365 387	117 094
Heating energy consumption - gas		245 000	0
Heating energy consumption - diesel fuel		0	36 068
Heating energy consumption - wood		0	47 325
Transport		11 275	3 383
Labour		149 940	44 982
External services		47 200	0
Total variable or direct costs, C_V [€/ha]		573 802	165 459
Investment cost [€/m^2]	Amortization [€/ha]	**74.8**	46 607
Total fixed or indirect costs C_F [€/ha]		42 000	26 000
Total cost [€/ha]		**662 409**	**238 066**
Unitary cost [€/kg]		1.32	1.59
Average price A_P [€/kg]		1.65	1.65
Total value crop [€/m^2]		82.7	24.8
Production value P_V [€/ha]		**826 500**	**247 950**
Annual operating income I_Y [€/ha]		164 091	9 884

Energy consumption for heating is much higher in these greenhouses, between 9000-13000 GJ/ha than those required in Almería, with a more temperate climate.

Table 19. Energy and water consumption estimated for a commercial multispan high-tech greenhouses heated with natural gas and measured in a greenhouse heated with diesel and wood pellets (by Sfera Agricola) in Italy for the season 2022/23.

Heating energy source	**Natural gas**	**References**	**Diesel and wood pellets**
Energy consumption			
Electicity price [€/kWh]	0.276	ARERA (2023)	0.210
Total electrical consumption [kWh/m^2]	15.0	Battistel (2014)	11.4
Electrical consumption [GJ/ha]	**540**	Calculated	**410**
Natural gas price [€/m^3]	0.980	ARERA (2023)	-
Natural gas consumption [m^3/m^2]	25.0	Battistel (2014)	-
Diesel fuel price [€/m^3]	-	-	1.050
Diesel fuel consumption [L/m^2]	-	-	3.44
Wood price [€/tons]	-	-	75.0
Wood consumption [kg/m^2]	-	-	63.1
Heating energy consumption [kWh/m^2]	270.8	Calculated	350.9
Heating energy consumption [GJ/ha]	**9 747**	Calculated	**12 631**
Water consumption			
Water consumption [m^3/ha]	10 000	Battistel (2014)	300
Water price [€/m^3]	0.25	CBTC (2024)	0.25
Water requirements [m^3/t]	**20.0**	Calculated	**2.0**

These greenhouses generate higher emissions of around 1400 kg CO_2 eq/tn.

Table 20. Total environmental impacts factors provided by the EXCEL EUPHOROS environmental simulation model (Torrellas et al., 2013) for "Cherry" tomato grown in commercial multispan high-tech greenhouses heated with natural gas and with diesel and wood pellets in Italy for the season 2022/23 by functional unit (1 tonne of marketable tomatoes).

Heating source	**Natural gas**	**Diesel and wood pellets**
Yield [kg m^{-2}]	50.00	15.00
ADP - Abiotic depletion [kg Sb eq/tn]	11.79	9.72
AAP - Air acidification [kg SO_2 eq/tn]	2.50	5.16
EUP - Eutrophication [kg PO_4eq/tn]	1.16	2.01
GWP - Global warming [kg CO_2 eq/tn]	1 444.0	1 415.6
POP - Photochemical oxidation [kg C_2H_4/tn]	0.15	0.24
CED - Cumulative energy demand [MJ/tn]	25 552	24 120
Water consumption [m^3/tn]	20.00	2.00

3.7. Conclusions

In heated greenhouses of Spain and Italy thermochemical fluids could be used to reduce the cost of heating energy and to reduce their environmental impact.

The climate control system based in thermochemical fluids could be used in unheated multispan greenhouses to cooling and humidity control.

The medium-large sized companies (20-50 ha) are the most susceptible to incorporating this type of technology in Spain.

The farmers consulted indicated that they would make an investment of 5 000-15 000 €/ha with a return period of 2-10 years.

4. TheGreefa impacts

The section of TheGreefa Training Manual focuses on presentation the results of the analysis of the environmental and economic impacts related to the implementation of TheGreefa technology in greenhouses. The main technology being analysed is the indoor climate control system for greenhouse application.

4.1. Environmental impact

In TheGreefa project, the potential environmental benefits related to implementation of TheGreefa technology in greenhouses have been identified in the Life Cycle Analysis performed within the Work Package 3 of the project, focusing on evaluation of the developed technologies.

The study was conducted in accordance with the principles and framework for LCA, which are defined in the international standard for LCA, ISO 14040 and ISO 14044.

Data from TheGreefa demonstrators and case studies were collected to be analysed in terms of energy, water, fossil fuels consumption and production of the greenhouses to compare the environmental impacts before and after implementation of TheGreefa system based on real data (demonstrators) or simulations (case studies). The LCA study allows to analyse and present overall long-term efficiency of TheGreefa technology and how it can have a positive impact on the environment and people.

The LCA was conducted based on real data obtained from TheGreefa greenhouses located in midcontinental climate zone (Switzerland) and Mediterranean climate zone (Italy, Tuscany).

LCA methodology

There are four distinct steps in an LCA study, described in the mentioned ISO standards.

The 1st one is the definition of the goal and scope of the study, to ensure that the LCA is performed consistently.

- LCA models a product, service, or system life cycle. A model is a simplification of a complex reality and as with all simplifications, this means that the reality will be distorted in some way. The challenge for an LCA practitioner is to make sure the simplification and distortions do not influence the results too much. The best way to do this is to carefully define the goal and scope of the LCA study.

Then, we can move to the 2nd step, the inventory analysis of extractions and emissions step.

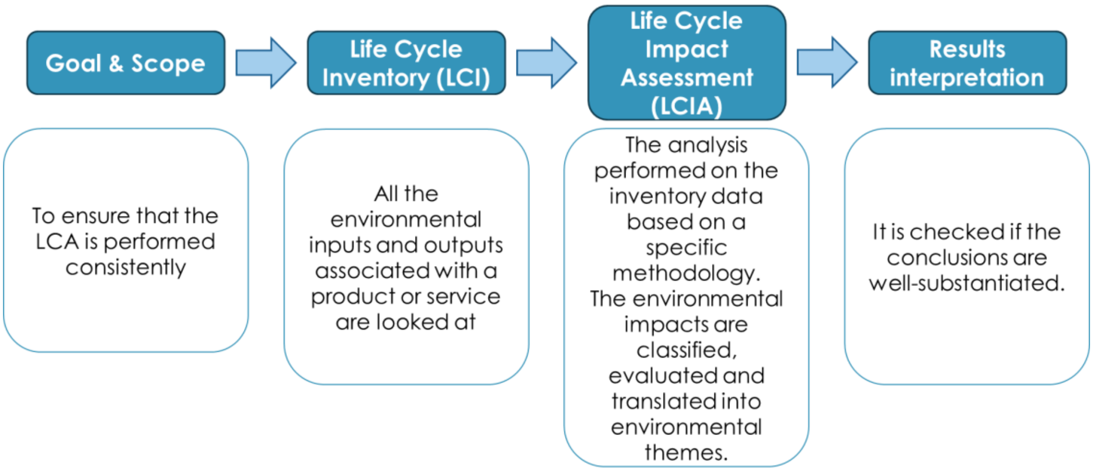
- In the inventory analysis, all the environmental inputs and outputs associated with a product or service are looked at. An example of an environmental input – something that is taken out of the environment to put into the product's life cycle – is the use of raw materials and energy. Environmental outputs – which the product's life cycle puts out into the environment – include the emission of pollutants and the waste streams. Together, they give the complete picture of the product's or process' life cycle.

Having the inventory completed, we can move to the life cycle impact assessment step.

- In the life cycle impact assessment (LCIA), the conclusions that allow to make better business decisions are drawn. The environmental impacts are classified and evaluated by what is most important to a company and translated into environmental terms such as global warming or human health. The most important choice that needs to be made is how integrated the results should be. There is an option of a single score to show how sustainable the product is, or to be able to see whether the design improves on CO_2 emissions and other climate change factors. This usually depends on the type of audience to be addressed and the ability of the audience to understand detailed results.

As the final – 4th step, we need to the interpret the results obtained in the previous step.

- During the interpretation phase, it is checked if the conclusions are well-substantiated. The ISO 14044 standard describes several checks to test whether conclusions are adequately supported by the data and by the used procedures.



To ensure that the LCA is performed consistently

All the environmental inputs and outputs associated with a product or service are looked at

The analysis performed on the inventory data based on a specific methodology. The environmental impacts are classified, evaluated and translated into environmental themes.

It is checked if the conclusions are well-substantiated.

Figure 50. Four steps in performing an LCA.

For TheGreefa project, the goal of the LCA study was to analyse and compare the environmental impacts resulting from 15 years of the greenhouses operation, considering the greenhouse before and after the implementation of TheGreefa climate control system.

LCA boundaries			Life cycle stages	Life cycle stage designation and description	
Cradle to cradle (C2C)	Cradle to grave (C2G)	Cradle to gate	Product stage	A1	Raw material extraction and processing, processing of secondary material input
				A2	Transport to the manufacturer
				A3	Manufacturing
			Installation process stage	A4	Transport to the Building site
				A5	Installation into the Building site
		Gate to grave	Use stage – information modules related to the Product/Material	B1	Use or application of the installed product
				B2	Maintenance
				B3	Repair
				B4	Replacement
				B5	Refurbishment
			Use stage – information modules related to the operation of the Customer site	B6	Operational energy use
				B7	Operational water use
			End-of-life stage	C1	Deconstruction, demolition
				C2	Transport to waste processing
				C3	Waste processing for reuse, recovery and/or recycling (3R)
				C4	Disposal
			Benefits and loads beyond the system boundary	D	Reuse, recovery and/or recycling (3R) potentials

Figure 51. Life cycle stages of a product or service.

Then the boundaries of the analysis must be defined. The table presents the boundaries including all the life cycle stages of the product or service. From acquisition of the raw materials through manufacturing, use, dismantling, up to final disposal or recycling of materials.

In the analysis, for each greenhouse the 15 years long operation period is studied for 1 ha area of the greenhouse. Therefore, only the operation stage of the life cycle is considered to identify and compare the impacts. The differences are related to energy and fuel consumption by the greenhouses' energy systems in their operation.

SimaPro software was used to perform the analysis.

Impact categories

The ISO standards define the specific categories io impacts describing the environmental loads. The main impact categories considered in the LCA are:

- **Abiotic depletion potential** – referred to the consumption of non-biological resources such as fossil fuels, minerals, metals, water, etc. It indicates the decrease of such resources. The category is expressed in units MJ for fossil fuels and in kg of antimony (Sb) equivalent for other minerals.
- **Climate change / Global Warming potential** – defined as the change in global temperature caused by the greenhouse effect that the release of "greenhouse gases" by human activity creates.
- **Ozone Layer Depletion potential** – degradation of the stratospheric ozone layer due to anthropogenic emissions of ozone depleting substances. It can cause increase of ultraviolet UV-B radiation and number of cases of skin illnesses.
- **Human Toxicity potential** – a calculated index that reflects the potential harm of a unit of chemicals released into the environment, and it is based on both the inherent toxicity of a compound and its potential dose. These by-products, mainly arsenic, sodium dichromate, and hydrogen fluoride, are caused, for the most part, by electricity production from fossil sources.
- **Freshwater Aquatic Ecotoxicity potential** – the toxic effects of chemical on ecosystems, in this case in the freshwater, causing biodiversity loss and/or species extinction.
- **Marine Aquatic Ecotoxicity potential** – the toxic effects of chemical on ecosystems of marine reservoirs, causing biodiversity loss and/or species extinction.
- **Terrestrial Ecotoxicity potential** – the toxic effects of chemical on land ecosystems, causing biodiversity loss and/or species extinction.
- **Photochemical Oxidation potential (Photochemical ozone creation potential)** – defines the potential for creation of the type of smog created from the effect of sunlight, heat and non-methane volatile organic compounds (NMVOC) and nitrogen oxides (NOx).

- **Acidification potential** – reduction of the pH due to the acidifying effects of anthropogenic emissions. It is related with emissions of gases such as NH_3, NO_x and SO_x, which mixes with water in the atmosphere and causes acid rains increasing then the acidity of water and soil systems.
- **Eutrophication potential** – defines potential for accumulation of nutrients in aquatic systems. The impact indicators are the increase of nitrogen and phosphorus concentration and formation of biomass (e.g. algae).

Life cycle inventory – Swiss greenhouse

The Meyer Orchideen greenhouse is TheGreefa demonstrator, where the real scale system is implemented and in operation. In the greenhouse of Meyer Orchideen AG in Switzerland, being close to the Zurich airport, there were demonstrated TheGreefa humidity control, heating and cooling in one system through a single process.

Figure 52. Meyer Orchideen greenhouse

The greenhouse in the analysis has the area of 600 m^2, where there are 9 air conditioning units (absorbers) implemented, each of the power of 8 kW as heat/cooling capacity, each supplying approximately 50 m^2 of planting tables.

Figure 53. The absorber unit (left) and planting tables (right) in the greenhouse in Switzerland.

The TCF used in the project is $MgCl_2$. All the 9 systems are served by desorber installed outside the greenhouse. The energy systems are integrated with the renewable system of the greenhouse, including wood boiler, ground-water heat pump, photovoltaic panels and well water.

Solar energy is used for TCF regeneration and buffer storages are installed to store diluted and concentrated TCF.

The data collected for the environmental evaluation was supposed to allow to compare the impacts such as environmental impacts or human health impacts between the 600 m^2 greenhouse operating without TheGreefa system and with the system implemented in a period of 15 years. The analysis has been performed for a reference unit of 1 ha of the analysed greenhouse. Therefore, the collected inputs required recalculation for 1 ha area and the designed period of time.

The focus was on inputs allowing comparison of the energy efficiency of the greenhouse, considering used electricity, water and fuels. Most of the water in the greenhouse is used in a closed cycle or is recovered from rainfall. Water needed for cooling process was included in the analysis.

In Table 21 in the slide, the initial data provided by Zurich University of Applied Sciences are presented, with the help of which IZNAB carried out further calculations, such as the determination of the weight quantity of fuels, the number of transports. These data were necessary for the analysis with the SimaPro software. Besides SimaPro database, the Ecoinvent database was used in the analysis to provide necessary inputs and outputs in technological processes of the greenhouse lifecycle.

Table 21. Energy and fuel consumption data collected from the Swiss greenhouse.

	1 season for 600 m^2 greenhouse		**1 season for 1 ha greenhouse**	
	Standard greenhouse	**TheGreefa system**	**Standard greenhouse**	**TheGreefa system**
Electricity consumption (pumps, fans and heat pump)	43 178.69 kWh	39 945.54 kWh	719 645 kWh	665 792 kWh
Oil consumption	1 350 kWh	320 kWh	22 500 kWh	5 333 kWh
Wood consumption	228 150 kWh	54 080 kWh	3 802 500 kWh	901 333 kWh
Water consumption	0 m^3	23 m^3	0 m^3	383.3 m^3

Life cycle inventory – Italian greenhouse

The next case is the Italian greenhouse system of Sfera Agricola which represents the high technology system and one of the new methods of high-quality agriculture production. It performs a case study with water recovery and energy efficiency in greenhouses. The greenhouse is in South Tuscany in Italy.

The case study of the Sfera company represents an ideal example of the challenges of intensive and high-quality Mediterranean agriculture, particularly in the important challenge areas of water and energy efficiency. The greenhouse took the role of a case study in TheGreefa project. The aim of the case study activities is to analyse the data collected during the year, depending on the climatic variations and the cultural needs of the greenhouse, to define the best design needs to further reduce energy costs and improve quality and productivity.

The data collected for the environmental assessment are results of simulations performed by TheGreefa project partners. The data represents a full season of operation of 1 ha greenhouse area.

Figure 54. Sfera Agricola's greenhouse – roof system (top left), piping heating system (top right) and the tomato plants with sensors (bottom).

The heat in the greenhouse is supplied with wood and oil boilers. The system has a power of 7,000 kW. The main types of wood used as fuels are fir, pine, holm oak and chestnut. The oil consumption is approx. 600 l/h. The heating system consumes about 28% of the electricity used by the greenhouse, mainly for auxiliary equipment, such as pumps.

Table 22. Energy and fuel consumption data collected from the Italian greenhouse.

	Standard system	**TheGreefa**
Heating season	**1 year for 1 ha greenhouse**	
Electricity	90 330 kWh	99 363 kWh
Oil	34 350 l	27 480 l
Wood	631 t	505 t

Life cycle assessment

Both the greenhouses mentioned above have been assessed considering two scenarios:

- Scenario 1_Existing greenhouse (before modernisation). The life cycle analysis for the greenhouse has been carried out before the implementation of TheGreefa system.
- Scenario 2_Retrofitted greenhouse (after modernisation). The life cycle analysis for the greenhouse has been carried out after the implementation of TheGreefa system.

Swiss greenhouse

Firstly, the results of the environmental assessment are presented for the Swiss greenhouse. Performing the LCA calculation using CML-IA baseline methodology, the results are given for the main impact categories. In each category the positive impact of the implementation of TheGreefa system in the greenhouse can be observed – lower or higher. The impacts reduction in case of TheGreefa system operating can reach between 37% up to 76%.

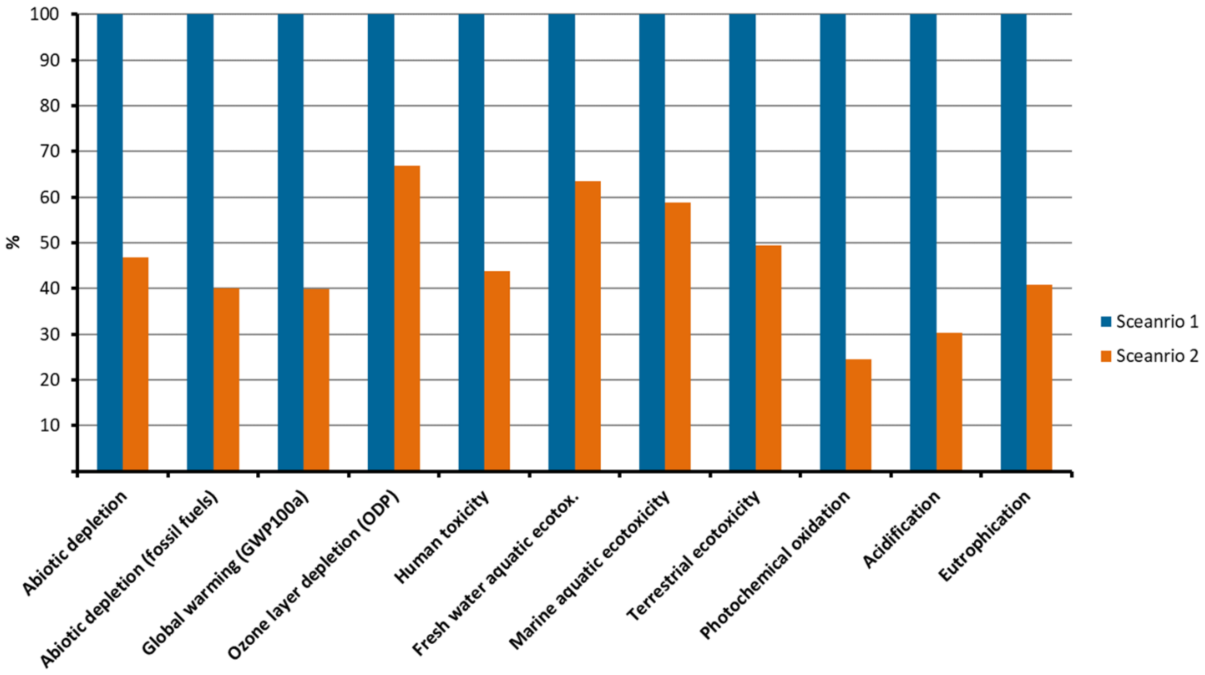


Figure 55. Environmental assessment: Swiss demonstrator – Scenario 1 & Scenario 2 compared (SimaPro 8.3.0). Method: CML-IA baseline V3.04 / EU25 / Characterisation for impact categories.

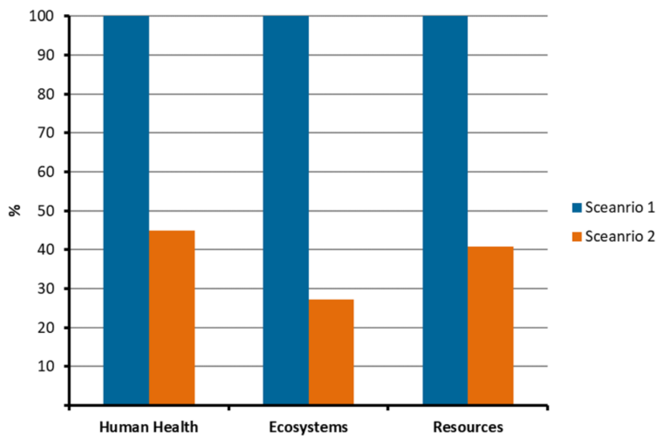


Figure 56. Comparing the damage assessment: Swiss demonstrator – Scenario 1 & Scenario 2. Method: ReCiPe Endpoint (E) V1.13 / Europe ReCiPe E/A.

For better presentation another analysis was performed using the European ReCiPe Endpoint methodology. It presents the impacts grouped in 3 main factors – Human Health, Ecosystems and use of Resources.

Based on the achieved results, 15 years of TheGreefa system operation in the Swiss greenhouse may result in approx. 55% reduction in the human health impacts, 60% reduction in case of the resources depletion and approx. 73% reduction of the impacts on ecosystems.

The compared operational stages for both scenario and their environmental impacts are mainly dominated by the energy consumed in the greenhouse in different forms – electricity and heat.

Another way of presenting the environmental benefits is specifically analysis of the Global Warming Potential category expressed in equivalent of kg of CO_2 emitted. In terms of CO_2, during the 15 years TheGreefa technology will allow to save 2 680 tons of CO_2 emissions from 1 ha of the greenhouse. In terms of percents it gives a global warming potential reduction of around 60%. However, the mass of CO_2 and the percentage should also make it clear what an intensive industry greenhouse cultivation is.

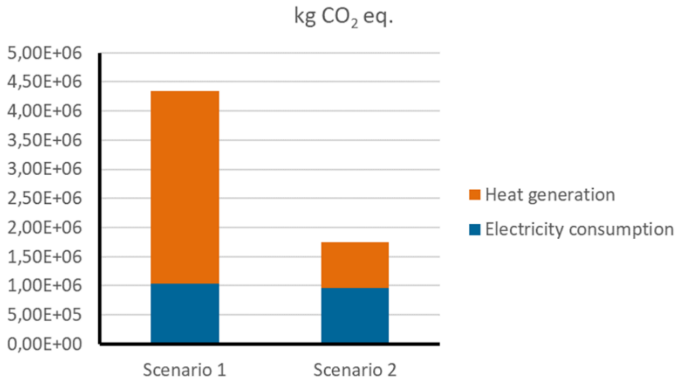


Figure 57. Global Warming Potential (GWP) of the Swiss demonstrator in both scenarios.

Italian greenhouse

Now, moving to the Italian case, using CML-IA baseline methodology, similarly as for the Swiss demonstrator, in each category the positive impact of the implementation of TheGreefa system in the greenhouse can be observed for the Italian case study too. However, in the Italian greenhouse the reduction of impacts is less visible in the graph, as for each category the reduction varies between 10-20%.

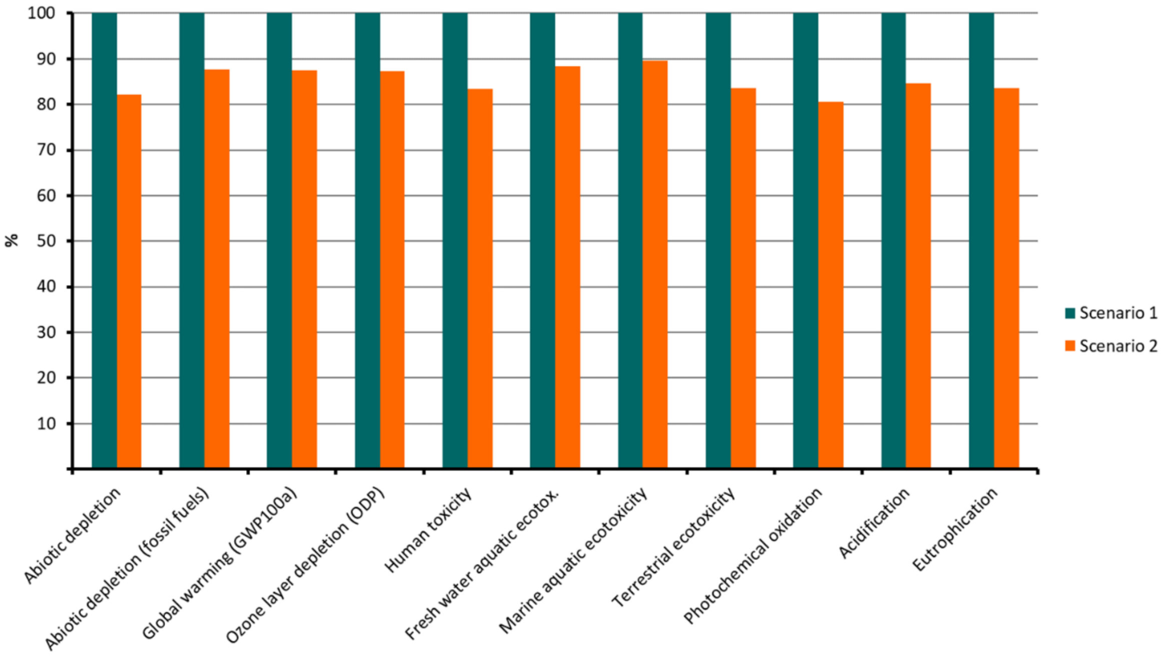


Figure 58. Environmental assessment: Italian case study – Scenario 1 & Scenario 2 compared (SimaPro 8.3.0). Method: CML-IA baseline V3.04 / EU25.

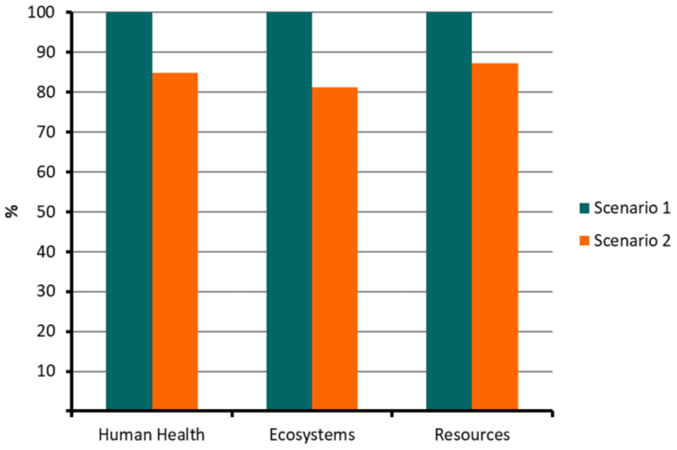


Figure 59. Comparing the damage assessment: Italian case study – Scenario 1 & Scenario 2. Method: ReCiPe Endpoint (E) V1.13 / Europe ReCiPe E/A.

Using the European ReCiPe Endpoint methodology, 15 years of TheGreefa system operation in the Italian greenhouse may result in approx. 15% reduction in the human health impacts, 13% reduction in case of the resources depletion and approx. 19% reduction of the impacts on ecosystems.

Also in this case, the environmental impacts are mainly dominated by the energy consumed in the greenhouse in different forms – electricity and heat.

In terms of CO_2 savings, TheGreefa technology will allow to save over 362 tons of CO_2 emissions from 1 ha of the greenhouse in 15 years operation period. In percentage, it gives a global warming potential reduction of almost 13%.

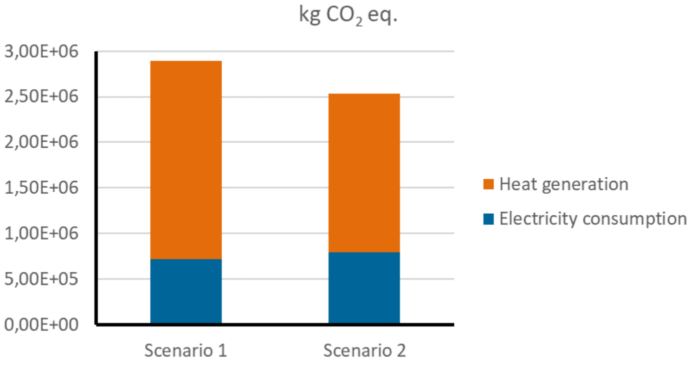


Figure 60. Global Warming Potential (GWP) of the Italian case study in both scenarios.

4.2. Economic impact

The economic impact of TheGreefa was analysed in the technoeconomic evaluation performed on the indoor climate control system. The study has been performed in close relation to the environmental assessment presented in section 4.1. The same data about energy and fuels consumed in TheGreefa greenhouses were used in the economic study, additionally considering also information about costs related to the energy and fuels. The outputs of the study were supposed to be estimation of possible return of investment period for implementation of TheGreefa system, as well as suitable cost of the system itself offering acceptable return of investment. Another result of the analysis is evaluation of viability of implementation of the system in greenhouses in different climate zones.

Performing calculations for a greenhouse for two scenarios gives annual cost savings of a greenhouse comparing the greenhouse operation with and without TheGreefa system. To compare the greenhouses of the project, the collected data were processed for comparison of 1 ha area of the greenhouses.

The data collection was available for one TheGreefa demonstrator – Meyer Orchideen's greenhouse in Switzerland, and one case study – Sfera Agricola's tomato greenhouse in Italy.

Cost inputs for the economic evaluation

The environmental data used for the study has been already presented in the previous section. Here the cost data has been collected.

Swiss greenhouse

The heat energy for the greenhouse is delivered from an external company. The greenhouse owner pays the prices for delivered energy, as follows: €96/MWh of heat from oil and €45.12/MWh of heat from wood. The electricity cost is €197.76/MWh.

The data collected for the evaluation was supposed to allow to compare the economic impacts between the 600 m^2 greenhouse operating without TheGreefa system and with the system implemented in a long-term period of operation. The analysis has been performed for the 600 m^2, as well as for a reference unit of 1 ha of the analysed greenhouse. Therefore, the collected inputs required recalculation for 1 ha area.

In terms of the investment cost relate to the implementation of TheGreefa system in the Swiss greenhouse, the cost was €153 600. Breaking down this cost into the cost of materials and labour, the ratio is estimated to be 50/50. In Switzerland, the labour cost used in the study is €120/hour. The investment cost represents implementation of the system in the 600 m^2 greenhouse.

Table 23. Seasonal input for the Swiss greenhouse – 600 m^2.

	Standard greenhouse	**Cost**	**TheGreefa system**	**Cost**
Electricity consumption (pumps, fans and heat pump)	43.18 MWh	€8 539.02	39.95 MWh	€7 900.03
Oil consumption	1.35 MWh	€129.60	0.32 MWh	€30.72
Wood consumption	228.15 MWh	€10 294.13	54.08 MWh	€2 440.09

Table 24. Cost of implementation of TheGreefa system in the 600 m^2 Swiss greenhouse.

Materials cost	€76 800.00
Labour cost	€76 800.00
Total investment cost	€153 600.00

As mentioned, to be able to compare the results of the study with the 1ha Italian greenhouse, the costs and consumption of energy and fuels were calculated for 1 ha. Then the investment cost is €2 560 000.

Table 25. Seasonal input for the Swiss greenhouse – 1 ha.

	Standard greenhouse	**Cost**	**TheGreefa system**	**Cost**
Electricity consumption (pumps, fans and heat pump)	719.65 MWh	€142 317.98	665.79 MWh	€131 666.63
Oil consumption	22.50 MWh	€2 160.00	5.33 MWh	€511.68
Wood consumption	3 802.50 MWh	€171 568.80	901.33 MWh	€40 668.01

Table 26. Estimated cost of implementation of TheGreefa system in the 1 ha Swiss greenhouse.

Materials cost	€1 280 000.00
Labour cost	€1 280 000.00
Total investment cost	€2 560 000.00

Italian greenhouse

The heat in the greenhouse is supplied by wood and oil boilers. The system has a power of 7 000 kW. The main types of wood used as fuels are fir, pine, holm oak and chestnut. The oil consumption is approx. 600 l/h. The heating system consumes about 28% of the electricity used by the greenhouse, mainly for auxiliary equipment, such as pumps. The unit costs of energy and fuels provided by Sfera are: €0.22 per 1 kWh of electricity, €1.05 per 1l of oil and €75 per 1t of wood. The estimated annual cost of transport of fuels is €5 000.

Table 27. Seasonal input for the Italian greenhouse – 1ha.

	Standard system	**Cost**	**TheGreefa system**	**Cost**
Electricity	90 330 kWh	€19 872.60	99 363 kWh	€21 859.86
Oil	34 350 l	€36 067.50	27 480 l	€28 854.00
Wood	631 t	€47 325.00	505 t	€37 860.00

In terms of the investment cost, it was estimated based on the cost in the Swiss greenhouse. The same ratio of materials and labour costs were used. In terms of the labour cost, it is cheaper in Italy compared to Switzerland, and it is €40/hour. The €2 560 000 of the investment cost for 1ha Swiss greenhouse was taken as a base for calculation. It gives around €426 600 as the labour cost. Including materials, the total value of the investment cost for the Italian greenhouse is €1 706 600.

Table 28. Estimated cost of implementation of TheGreefa system in the 1 ha Italian greenhouse.

Materials cost	€1 280 000.00
Labour cost	€426 000.00
Total investment cost	€1 706 600.00

Technoeconomic evaluation

To be able to perform the technoeconomic evaluation of the TheGreefa system implementation, the two greenhouses has been analysed in two scenarios:

- Standard system – The greenhouse operation before the implementation of TheGreefa system.
- TheGreefa system – The greenhouse operation with TheGreefa climate control system implemented.

Swiss greenhouse

The return of investment period simulation was calculated considering annual expenses of the greenhouse operation (energy systems) with the standard system and with TheGreefa system. Calculated annual cost savings are €8 591.91. Based on the simulation and considering the investment cost of €153 600, the return of investment period is 18 years. Such amount of time is acceptable and expected by both the owner of the Meyer greenhouse, as well as the Swiss Federal Office of Energy collaborating in the demonstration of the Swiss greenhouse.

The achieved return of investment period is acceptable for the greenhouse owner. However, in market study of TheGreefa project, it was identified the most expected and acceptable time for most of greenhouses is 7-10 years. The Figure 61 below, the results of simulation are presented where other investment cost's values, and their return of investment periods were checked.

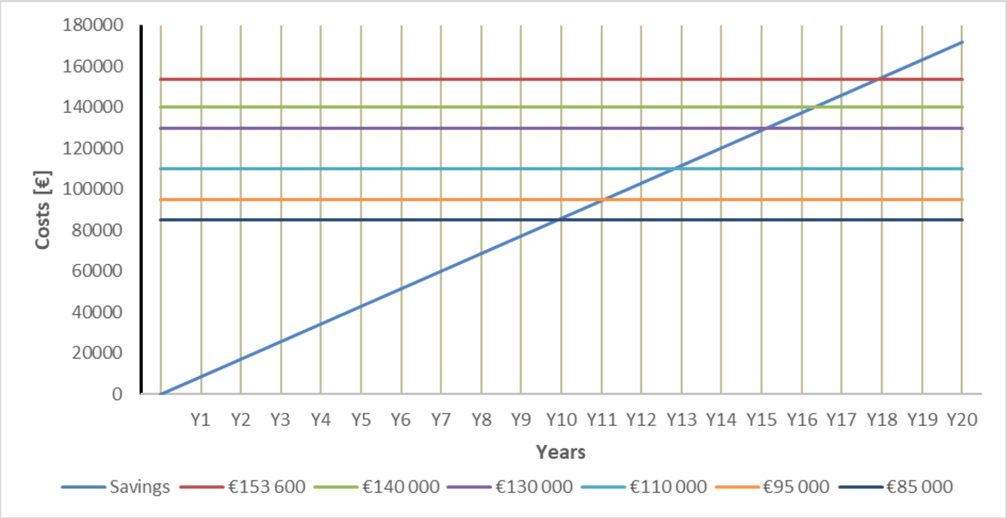


Figure 61. Return of investment period simulation for different investment costs – 600 m^2 Swiss greenhouse.

The goal is to find what should be the investment cost to meet the mentioned range of the expected time for the investment return. The initial value is €153 600 giving the period of 18 years. Limiting the cost to €110 000, the return of investment can be achieved in 13 years. However, only if the cost is almost 2 times lower than the initial value (€85 000) the expected time of 10 years is achieved.

For the comparison purpose the simulation was performed also for 1 ha Swiss greenhouse. The estimated investment cost for such case is €2 560 000. In this case the return of investment period is also 18 years.

Italian greenhouse

The return of investment period simulation was calculated considering annual expenses of the greenhouse operation (energy systems) with the standard system and with TheGreefa system. Calculated annual cost savings are €14 691.24. Based on the simulation and considering the investment cost of €1 706 600, the return of investment period over 100 years. Such long period is totally unacceptable and unachievable in real life. The long period is caused by proportionally small cost savings compared to the Swiss greenhouse analysed earlier. In case of the indoor climate control system for greenhouses in TheGreefa project it aims to reduce the heat losses and reduce the electricity and fuels consumption for providing the heat demand of the greenhouse. The higher is the heat demand of the greenhouse, the higher the savings resulting from the system implementation. It was identified during analysis of both Swiss and Italian greenhouses, the heat demand of the Italian case is 10 times lower than of the Swiss case. The difference is of course caused by the location in different climate zones. The proportion is also visible comparing the cost savings. For 1 ha greenhouse in Switzerland the cost saving is €143 200.46 each year, while for 1 ha Italian greenhouse it is only €14 691.24.

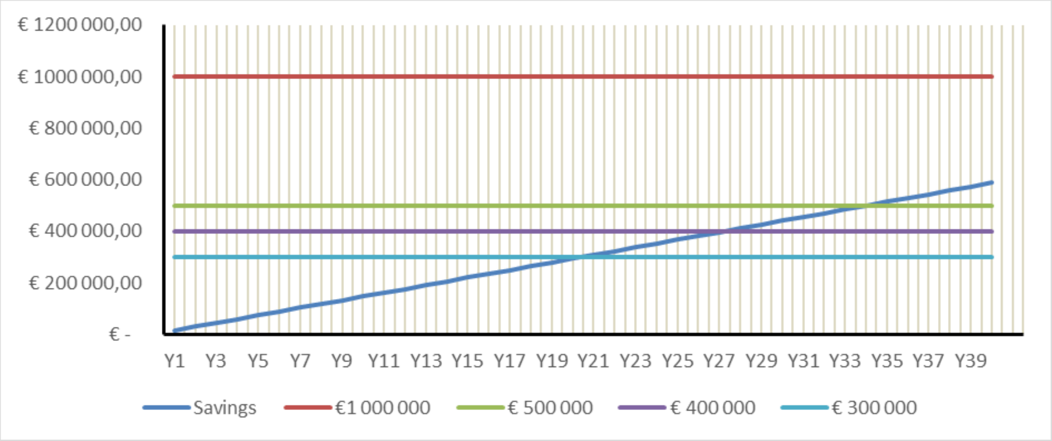


Figure 62. Return of investment period simulation for different investment costs – 1 ha Italian greenhouse.

The simulation was also performed to see what the cost of the system should be to have comparable return of investment period as the Swiss greenhouse. The results presented in Figure 62 shows only if the cost of the system implementation is €300 000, then the return of investment period is 21 years. However, for now such cost is not possible to be achieved for 1 ha greenhouse.

4.3. Conclusions

The results obtained in the presented Life Cycle Analysis (LCA) have shown that the use of the new TheGreefa technology in greenhouses contributes to visible lowering the environmental impacts of the greenhouse operations. The heating, cooling and humidity control are very energy intensive processes in the greenhouse operation. The heat production and electricity consumption are responsible for most of the environmental loads. Therefore, implementation of improvements in these aspects is the right call that can help to reach the EU climate goals by reduction of the use of electricity and natural resources.

Besides lower greenhouse gases emissions (CO_2 savings) are not the only benefits of the implementation of TheGreefa system. They are of course responsible for the climate change. But there are other aspects where TheGreefa brings improvements in the long-term period of operation. By big reduction of such factors as human toxicity or photochemical oxidation potentials, the use of the new system can result in 20% to over 50% reduction of the overall human health negative impact.

Use of resources like wood and oil, or even natural gas are lower, but can be lowered more when more renewable energy sources is implemented in the greenhouses' energy systems – heat pumps, geothermal energy, and other.

The technoeconomic evaluation gave promising results in case of the Swiss greenhouse of TheGreefa project located in Mid-continental climate. The investment cost of the implementation of the project's technology will give estimated return of investment period of 18 years. If the cost of implementation of TheGreefa system would be almost half lower (€85 000 for 600 m^2 greenhouse and €1 416 000 for 1 ha greenhouse), it could give the return of investment period of 10 years or lower.

As for the Italian greenhouse, the study has shown TheGreefa system with its current cost cannot offer acceptable return of investment period. The greenhouse heat demand is too low to cause the cost saving able to cover the cost of implementation of the new system.

As TheGreefa system is still not ready to enter market as a product, there is still a chance, and attempts will be made to reduce the cost of the system. Also, it should be considered to analyse possible limitations in terms the requirements of the greenhouses where the system could be implemented. Firstly, the heat demand of the greenhouse should be analysed. The study of the Swiss greenhouse can be used then as a baseline for classification of possible implementation options.

5. Social aspects and policies

Taking into account the field of application and the advantages offered by the technology proposed in the project, the policy recommendations must be based on the review of five fundamental areas: agriculture, energy, water, chemicals and food safety. In this presentation, we are going to see the main strategic and regulatory documents in each of these areas at the European level and then, on that basis, we will identify some policy recommendations which we believe that could facilitate the deployment of the proposed technology.

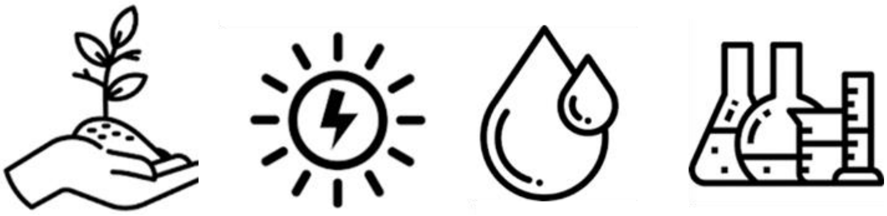


Figure 63. Main areas to base the review of policies – agriculture, energy, water and chemicals.

5.1. European strategic framework in agriculture

Climate change and environmental degradation are an existential threat to Europe and the world. To overcome these challenges, the European Green Deal aims to transform the EU into a modern, resource-efficient and competitive economy, ensuring no net emissions of greenhouse gases by 2050, economic growth decoupled from resource use, and no person and no place left behind.

The Farm to Fork Strategy is at the heart of the European Green Deal aiming to make food systems fair, healthy and environmentally-friendly. It promotes a more sustainable food system and it is among its main objectives to guarantee enough food, and that it is affordable and nutritious, without exceeding the limits of the planet.

A proposal for a legislative framework for sustainable food systems will be put forward to support implementation of the strategy and development of sustainable food policy.

The CAP 2023-27 entered into force on 1 January 2023. The approved Plans are designed to make a significant contribution to the ambitions of the European Green Deal, Farm to Fork Strategy and Biodiversity Strategy, with the modernization of agriculture through the development of more sustainable agricultural practices, while protecting nature and fighting climate change.

Among the tools that will further promote sustainable farming practices throughout the EU, the future CAP includes conditionality, which links area and animal-based CAP payments to a range of obligations. In addition, it also introduces the new ‘eco-schemes’ that aim to reward farmers for going further in the implementation of sustainable agricultural practices. These practices could include the implementation of environmentally friendly production systems such as agroecology, agroforestry and organic farming. The rural development framework also includes environmental and climate management commitments, which aim to compensate farmers and other beneficiaries for voluntarily committing themselves to implement sustainable practices.

5.2. European regulatory framework in energy

Directive 2023/1791 significantly raises the EU’s ambition on energy efficiency, making it binding for EU countries to collectively ensure an additional 11.7% reduction in energy consumption by 2030, compared to the 2020 reference scenario projections.

It also gives "energy efficiency first principle" a legal standing for the first time, so that it must be considered by EU countries in all relevant policy and major investment decisions taken in the energy and non-energy sectors. Indeed, the higher level of ambition requires a stronger promotion of cost-effective energy efficiency measures in all areas of the energy system and in all relevant sectors where activity affects energy demand, such as agriculture.

Additionally, under this revised Directive, EU countries will need to ensure an appropriate level of competence for energy efficiency related professionals, aligning them with market needs and enforcing clearer and stricter requirements for the necessary competencies. This includes energy service providers, energy auditors, energy managers and installers.

Regulation (EU) 2017/1369 lays down a framework that applies to energy-related products or systems placed on the market or put into service. It provides for their labelling and the provision of standard information regarding energy efficiency, the consumption of energy and of other resources during use and supplementary information, thereby enabling customers to choose more efficient products to reduce their energy consumption. Its article 7.2 establishes that where Member States provide incentives for a product, they shall aim at the highest classes of energy efficiency.

The new renewables energy Directive raises the share of renewable energy in the EU's overall energy consumption to 42.5% by 2030 with an additional 2.5% indicative top up to allow the target of 45% to be achieved. Each member state will contribute to this common target.

Finally, we have to mention European Commission Recommendation of 14 March 2023 on Energy Storage – Underpinning a decarbonised and secure EU energy system (2023/C 103/01) sets out a list of recommendations to ensure greater deployment of energy storage.

5.3. European regulatory framework in water

Water Framework Directive recognizes that waters in the Community are under increasing pressure from the continuous growth in demand, and that it is necessary to achieve a further integration of protection and sustainable management of water into Community policy areas such as agriculture. Taken it into account, it promotes sustainable water use based on a long-term protection of available water resources.

The hydrological planning process is crucial to achieve this goal and it is based on the integrated planning of water resources management by basins or hydrographic districts. Member states shall ensure that a river basin management plan is produced for each river basin district lying entirely within their territory, and it must make the achievement of environmental objectives for the bodies of water and associated ecosystems compatible with attention to the demands for the different uses of water, both in sufficient quantity and quality.

Also, a program of measures must be established in order to achieve environmental objectives and Member States may include in it demand management measures, inter alia, promotion of adapted agricultural production such as low water requiring crops in areas affected by drought

On the other hand, we must refer to the economic-financial regime for water, based on the principle of cost recovery established in the WFD (=the cost of investments made by public authorities to enable the provision of water by individuals is recovered through payment for the use of water by the different end users) The application of this principle must be done in a way that encourages the efficient use of water and, therefore, contributes to the environmental objectives pursued, with an adequate contribution from the various uses, in accordance with the polluter pays principle, and considering at least supply, agricultural and industrial uses. Under this principle, the competent public administrations must establish mechanisms to pass on costs, which normally include bonuses for agricultural use when the application of good agricultural practices is demonstrated.

5.4. European regulatory framework in chemicals

REACH and CLP regulations affect to all companies that use chemicals in the course of his industrial or professional activities (downstream users), not only to the ones that produce or import chemicals.

According to these regulations, magnesium chloride is a mixture not classified as hazardous, but we can identify the following main obligations for the use of magnesium chloride in professional greenhouse farming:

- To only use the mixture in accordance with the risk control measures provided with the information received from the supply chain
- To ensure that workers have adequate information about the mixture

5.5. Conclusions

As we have been able to verify by the analysis we have carried out, the proposed technology is closely aligned with the strategic recommendations and the regulations that govern the areas affected by the project.

Nevertheless, we can identify the following policy recommendations to facilitate the deployment of the technology proposed by the project:

1. To ensure that professionals dedicated to energy efficiency know the proposed technology and understand the advantages it offers in terms of energy efficiency, in line with the new mandate of the Directive (EU) 2023/1791 of the European Parliament and of the Council, of 13 September 2023, on energy efficiency, to ensure an appropriate level of competence for energy efficiency related professionals.

2. The adoption by the Commission of a delegated act in accordance with Article 17 of the Regulation (EU) 2017/1369 of the European Parliament and of the Council of 4 July 2017 setting a framework for energy labelling, in order to supplement this Regulation by establishing detailed requirements relating to labels for the proposed technology, so that Member States can provide incentives for it according to article 7.2.

3. In river basin districts affected by drought, incorporation by Member States into the program of measures of the promotion of crops that require little water.

4. Consideration of the proposed technology by the competent public authorities as a good agricultural practice deserving of a bonus in the economic and financial water regime.

5. Training of workers in the safe use of magnesium chloride.

References

Website and Social Networks

https://thegreefa.eu

https://x.com/TheGreefa

https://www.linkedin.com/company/thegreefa/

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