Final report

itGrows 2.0 – Business Intelligence for resource reduction and energy audit in protected cultivation

EUDP file: 64017-0557

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1. Project details

Project title	Business Intelligence for resource reduction and energy management in protected cultivation (itGrows 2.0)
File no.	64017-0557
Name of the funding scheme	Energy Efficiency
Project managing company / institution	Danish Technological Institute
CVR number (central business register)	56976116
Project partners	Danish Technological Institute byGrowers Hjortebjerg Dansk Gartneri HortiAdvice Københavns Universitet NB Data Aarhus Universitet Food Aarhus Universitet Agro
Submission date	22 December 2020

2. Summary

2.1 Sammenfatning

I itGrows 2.0 er der udviklet et dedikeret energioptimeringssystem til brug i den avancerede væksthusproduktion. Målet har været at øge den energi- og ressourceeffektivitet som allerede er opnået i væksthuserhvervet i løbet af de seneste år. Der er udviklet 2 programmer. *InfoGrow 2.0* der er et webbaseret online program, der opsamler data fra gartneriernes klimacomputer og benytter data i et matematisk modelbaseret system (UniSim) til at genererer key-performance-indikators for væksthusproduktionens energiforbrug, klimaet i plantehøjde samt planternes fotosyntese. *InfoGrow 2.0* er tænkt til at indgå i gartneriernes energiledelses arbejde.

Virtual Greenhouse er et offline Excel baseret program til at simulere og analysere data fra væksthusproduktionen. Væksthusets opbygning beskrives detaljeret i *Virtual Greenhouse* sammen med den ønskede klimastyringsstrategi. Ud fra vejrdata simuleres et års produktion. Det er muligt at sammenligne forskellige væksthusteknologier (lamper, gardiner m.m.) samt forskellige klimastyringsstrategier Derved kan man undersøge, hvordan energiforbruget kan nedsættes, samtidig med at planteproduktionen kan optimeres eller fastholdes.

Programmerne bygger på et modelsystem (*UniSim*), der rummer matematiske modeller for energiforbrug, klima og planteproduktion. UniSim's væksthusmodeller bygger på mange års forskning gennemført i Danmark og flere andre lande. I projektet er systemet udbygget og testet. Der er bl.a. udviklet en model til estimering af de enkelte væksthuses energiforbrug ud fra fremløbstemperatur i væksthusets varmerør. Dette giver producenterne helt nye måder at kunne følge med i energiforbruget for derved at kunne nedsætte det med diverse tiltag der først kan testes i *Virtual Greenhouse*.

InfoGrow 2.0 og *Virtual Greenhouse* er blevet demonstreret på flere internationale messer og konferencer og møder stor interesse fra teknologileverandører, konsulenter og væksthusproducenter.

2.2 Summary

In itGrows 2.0, we developed a dedicated energy optimization system for use in advanced greenhouse production. The goal was to increase the energy and resource efficiency even further than had already been achieved by the greenhouse industry in recent years. Two softwares were developed: *InfoGrow 2.0* and *Virtual Greenhouse. InfoGrow 2.0* which is a web-based online program that collects data from the greenhouse climate computer and uses data in a mathematical model-based system (*UniSim*) to generate key performance indicators for greenhouse production energy consumption, plant height climate, and plant photosynthesis. *InfoGrow 2.0* is a decision support tool for horticultural energy management.

Virtual Greenhouse is an offline Excel-based program for simulating and analysing data from greenhouse production. The structure of the greenhouse is described in detail in *Virtual Greenhouse,* together with the desired climate management strategy. Based on weather data, one year of production is simulated. It is possible to compare different greenhouse technologies (lamps, curtains, etc.) as well as different climate management strategies. In this way, one can investigate how energy consumption can be reduced while at the same time, the plant production can be optimized or maintained.

Both softwares share a common model system (*UniSim*), which contains mathematical models for energy consumption, climate, and plant production. UniSim's greenhouse models are based on many years of research conducted in Denmark and several other countries. In the project, the system has been expanded and tested. Thus the project developed a model that estimate the energy consumption of a greenhouse based on the inflow temperature of the greenhouse heat pipes. This opens the opportunity for producers to keep up with energy

consumption. Measures to reduce energy consumption can be tested in the Virtual Greenhouse before implementation.

InfoGrow 2.0 and *Virtual Greenhouse* have been demonstrated at several international trade fairs and conferences and met great interest from technology suppliers, consultants and greenhouse manufacturers.

3. Project objectives

The purpose of the project was to address the need for a dedicated Energy Management System in advanced greenhouse production systems. The system should assist nurseries, both in their daily supervision of the energy system, as well as in their strategic planning aimed at reducing energy consumption. The developed Energy Management System combines two softwares for decision support: InfoGrow 2.0 and Virtual Greenhouse. InfoGrow 2.0 can be used to achieve energy use reduction by optimized greenhouse climate control; Virtual Greenhouse, which simulates greenhouse-crop systems, can be used as a basis for decisions on adjusting the climate control or on making investments in energy-saving measures.

Greenhouses for protected cultivation of horticultural crops have, over the centuries, evolved from simple structures using solar radiation to increase the indoor temperature and thereby extending the production season, into advanced production systems with the possibility to control the indoor climate (and with that, the crop) very accurately. Today, the typical greenhouse in Denmark and Western Europe is a structure of steel and aluminium, covered with sheet glass or highly insulating sheets of multi-layer polycarbonate. Inside, it is fitted with movable screens for energy saving during the night and shading during the day, fixtures for supplemental light, ventilation windows, pipe heating systems, and equipment to supply extra carbon dioxide for increased photosynthesis. All installations are controlled by an advanced climate computer, which also monitors the climate in the different sections of the nursery and provide alarms, if the climate variables are not within predefined limits.

The greenhouse, with all of its components, is an expensive production system and the grower must keep production levels high in order to secure the required rate of return on investment, which also entails using a considerable amount of energy for optimizing growth conditions. The energy efficiency of the greenhouse sector has improved gradually since the 1970s energy crisis, with the introduction of energy-saving screens and insulating covering materials, but energy remains a heavy expenditure in greenhouse production. Nurseries therefore continue to invest in energy-saving measures when a profitable investment can be identified and the necessary capital is available. To assist the nurseries when making decisions on these type of investments, the project developed a simulation tool (Virtual Greenhouse), which can simulate the effects of the planned investment for the specific greenhouse in terms of energy use, indoors climate effects and effects on crop production.

In many respects, greenhouse climate control is a trade-off between the desire to create the optimal conditions for the crop (avoiding plant stress) and the wish to save energy, resources and money. However, climate control systems still have great potential for further energy savings without too many negative effects on the crop, if handled intelligently; e.g., if some degree of fluctuation in air temperature can be accepted, the Dynamic Climate Control strategy has been identified earlier as a way to increase the utilization of solar energy and reduce energy consumption.

Humidity is one of the major challenges when it comes to climate control in greenhouse production. High levels of humidity can potentially decrease the nutrient uptake and, subsequently, the growth of the crop and increase the risk of disease, which can lead to the reduced quality or even a failed production. Great effort is therefore put into keeping humidity levels down, usually by ventilation and/or increased heating. It is estimated that humidity control can easily amount to 30 % of the annual energy consumption in a greenhouse nursery. If the humidity challenge is handled more effectively, there is a significant potential for energy savings to be made. The main source of humidity inside a greenhouse is plant transpiration. Hence, the key to reducing the humidity problem is to have solid models describing the relationship between crop transpiration and greenhouse microclimate.

In itGrows 2.0, our goal was to combine research and development across the disciplines of mathematical modelling, software engineering and plant physiology. Before the project started, earlier versions of InfoGrow and Virtual Greenhouse existed as separate tools. The project integrated and extended these tools, which resulted in a complete Energy Management System for protected cultivation. The strength of the new combined tool is a shared database with a unified modelling framework on top, based on UniSim developed by AU. The new software design should make it easier to adjust and extend the models in the framework. The new system should also be more user friendly, so that a minimum of support will be required. The vision was to make it easier for the grower to change between different crops and corresponding energy management strategies. We aimed to achieve this by combining plant physiological knowledge with image vision tools. The earlier Redhum project indicated a relationship between the outer appearance of a leaf and its potential transpiration (and photosynthesis), yet no model or technology had been developed to utilise incorporate this information. This project aimed to implement this knowledge, so that pictures taken with a mobile camera could be uploaded to a server and an estimate of the potential transpiration returned.

The project aimed at a high-tech, user-friendly software product, the itGrows 2.0 monitoring, analysis, and management system for the protected cultivation market. itGrows 2.0 should be a tool that can be connected to existing software services, such as Senmatic and PRIVA climate controllers, with applications in all types of protected cultivation systems. itGrows 2.0 should enable the producer to achieve optimal crop production in terms of product quality and energy savings.

4. Project implementation

The overall objective of the project was to develop a model-based decision support system that can be used to save energy in greenhouse production. The objective was divided into the development of the decision support software and traditional statistical analysis of the data collected by the software. Unfortunately, the software development was delayed significantly, and the transfer of data to our own cloud storage therefore also delayed. This changed our plans to put more emphasis on the development of the Virtual Greenhouse application. Consequently, instead of analysing the two participating greenhouse companies in detail, we developed an application that can be used generally to analyse the use of energy in greenhouse production. Virtual Greenhouse is described later, but it is an application that can work with data either collected by InfoGrow 2.0 or data exported directly from a climate computer.

The delay in software development, unfortunately, influenced several of the milestones in the project. At the end of the project, almost all milestones were fulfilled, or they will a few months after project closure. The only missing milestone concerns the use of InfoGrow 2.0 together with a foreign greenhouse grower. We are continuing the work in the project Greenhouse Industry 4.0 and are in contact with several growers who are interested in testing the software. We have, at the end of this project, agreed to install the software at a total of 10 nurseries. Three nurseries are planning to buy the software, and the rest are using the software as part of different projects.

The project obtained all the technical objectives defined from the start of the project. Our Virtual Greenhouse has been developed much more than we expected from the beginning. We are also meeting a very high interest in our work. Together with Senmatic (Danish manufacturer of greenhouse climate computers), we have presented our work at a webinar for their dealers around the world. The interest in the software is remarkable, and we have been asked to make tests of the software in both USA, Great Britain and Greece. We have presented the software for three Danish greenhouse producers that are not part of the project, and all three have said that they are interested in buying a license when we are ready. We also expect that the software will be an important feature for Senmatic when selling their technology on the world market and an important tool for HortiAdvice in the advisory service.

At the start of the project, we planned to used thermography as part of the climate control strategy. This was unfortunately not possible because of the greenhouse environment (see later for an extended explanation).

The project has participated in these international trade fairs with a demonstration of project results:

- GreenTech, 11-13 June 2019, Amsterdam, The Netherlands
- IPM Essen, 22-25 January 2019, Essen, Germany

It was also planned to take part in GreenTech 2020. This was unfortunately first postponed and later cancelled as a physical event due to the corona pandemic.

Figure 1. Photo from InfoGrow presentation at the GreenTech exhibition in Amsterdam 2019.

The project has participated in the following scientific conferences with the presentation of project results:

- ISHS International Horticultural Congress, 2018, 12-16 August, Istanbul, Turkey
- GreenSys 2019, 16-20 June, Angers, France

A conference was also planned in 2020 in Aarhus for a north European group of researchers and growers, but it was unfortunately also cancelled due to Corona.

Literature resulting from the project:

Bærenholdt, O. J., & Aaslyng, J. M. (2020). Det Virtuelle Væksthus. *Gartner Tidende*.

Baptiste, P. H. M. (2019). *Estimation of a change in stomatal conductance as a response to an environmental stress by mean of infrared thermography under greenhouse conditions* (Issue September). University of Copenhagen.

Fanourakis, D., Giday, H., Hyldgaard, B., Bouranis, D., Körner, O., & Ottosen, C. O. (2019). Low air humidity during cultivation promotes stomatal closure ability in rose. *European Journal of Horticultural Science*, *84*(4), 245–252. https://doi.org/10.17660/eJHS.2019/84.4.7

Fanourakis, D., Hyldgaard, B., Giday, H., Aulik, I., Bouranis, D., Körner, O., & Ottosen, C. O. (2019). Stomatal anatomy and closing ability is affected by supplementary light intensity in rose (Rosa hybrida L.). *Horticultural Science*, *46*(2), 81–89. https://doi.org/10.17221/144/2017-HORTSCI

Kjær, K. H., Aaslyng, J. M., & Pedersen, J. S. (2019). Digitale løsninger til væksthusproduktion. *Gartner Tidende*, 28–29.

Kjaer, K. H., Körner, O., Huet, J. M., Holst, N., Pedersen, J. S., & Aaslyng, J. M. (2020). An integrated simulation and decision support system for greenhouse climate control (InfoGrow 2.0) based on an open source greenhouse modelling platform. *Acta Horticulturae*, *1271*, 47–53. https://doi.org/10.17660/ActaHortic.2020.1271.7

Kjaer, K. H., 2020. Mål dig til et bedre væksthusklima. Gartnertidende 10, 34-35

Kuehn, A., & Aaslyng, J. M. (2020). Nye digitale muligheder i væksthus. *Gartner Tidende*.

Körner, O, Fanourakis, D., Tsaniklidis, G., Nikoloudakis, N., Chung-Rung Hwang, M., Larsen, D.H., Hyldgaard, B, Ottosen, C-O., Rosenqvist, R. 2020. Greenhouse energy optimisation through cultivar-specific evapotranspiration models: A case study in pot rose. Submitted to Biosystems Engineering

Project results

4.1 InfoGrow 2.0 and Virtual Greenhouse

A major part of the project's activities was to develop two new software systems, InfoGrow 2.0 and Virtual Greenhouse. Figure 2 presents an overview of the software developed in the project.

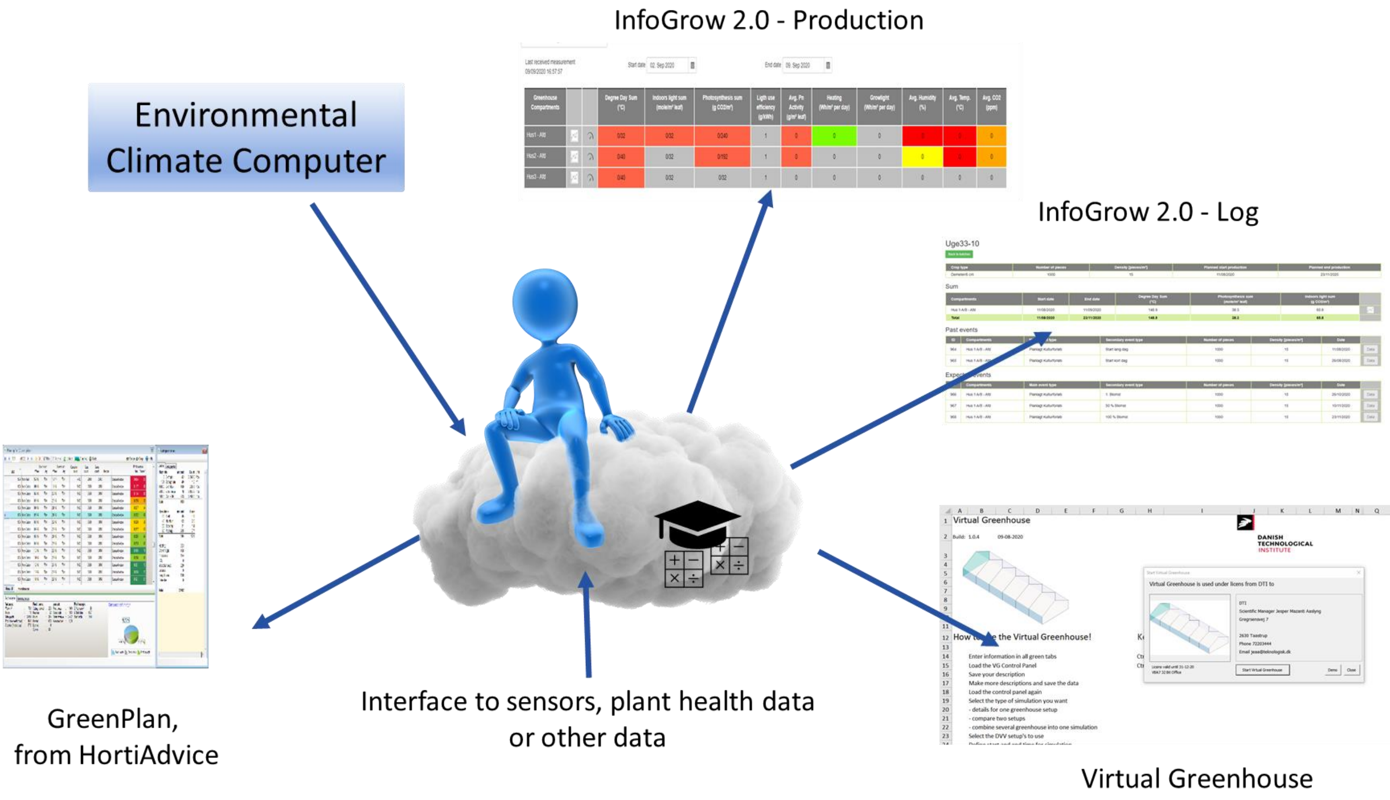

Figure 2. Overview of software developed in the project.

Climate data is collected with a data logger installed at the nursery. The **data logger** (a software module) was developed in the project. It can read data from both the Danish brand Senmatic and the Dutch brand Priva. Together Senmatic and Priva cover almost the total Danish greenhouse production.

In the cloud, the data are calculated using Universal Simulator (**UniSim)** developed at University of Aarhus[1]. In the project, we worked intensively with developing the plant and greenhouse model. UniSim calculates key performance indicators for greenhouse production. This includes indicators describing the use of energy, plant production as well as parameters indicating the light and energy use efficiency. The key performance indicators are shown in **InfoGrow 2.0 – Production** for all departments in the nursery. Colours are used to indicate if the values are above or below user-entered levels. To be able to utilize every possibility to lower the use of energy, it is essential for the growers to be able to control plant development from potting all the way to final product. To facilitate this we developed an **InfoGrow 2.0 – Log** that can be used as a production log, keeping track on development stage, use of pesticides, etc.

[1] www.ecolmod.org/download/

The mathematical models used for the calculations are common to InfoGrow 2.0 and **Virtual Greenhouse**. Virtual Greenhouse is a simulation system where the user describes both the greenhouse construction and the climate control strategy. With the use of weather data, the system simulates a yearly production with a focus on energy expenditures, plant production and plant climate. Climate data collected by InfoGrow 2.0 can be exported to Virtual Greenhouse and analysed there to identify possibilities for energy saving.

The system can also utilize data from **wireless sensors** from the company 30MHZ[2].

To release the potential of **InfoGrow 2.0 – Log,** we have been working with a connection to GreenPlan from HortiAdvise and NB Data. The interest from growers is remarkable, but unfortunately, this will first be finished after the project. We expect it to finish in April 2021.

4.2 InfoGrow 2.0

With InfoGrow 2.0, the grower gains real-time performance indicators for the use of energy, plant photosynthesis and plant growth. With this information, it is possible to adjust setpoints for climate parameters to optimize plant growth on a daily basis.

InfoGrow 2.0 has a log system that can be customized to the grower's needs. It is possible to register and report all data needed, e.g., application of biological or chemical pest control, product quality or development or production parameters. When data have been logged in InfoGrow 2.,0 they can be used later to document and optimize the production.

InfoGrow 2.0 uses data already collected by the climate computer to model plant photosynthesis, climate and energy. This makes InfoGrow 2.0™ unique as there is no need for costly installation of new sensors or fancy equipment.

The summary view displays data from all the climate zones of the greenhouse and uses colours to indicates where the focus is needed. Figure 3 shows the main screen of InfoGrow 2.0.

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[2] https://www.30mhz.com/news/your-greenhouse-in-the-palm-of-your-hand/

Greenhouse Compartments			Degree Sum (°C)	Indoors light sum (mole/m² leaf)	Photosynthesis sum (g CO2/m²)	Ligth use efficiency (g/kWh)	Avg. Pn Activity (g/m² leaf)	Heating (Wh/m² per day)	Growlight (Wh/m² per day)	Avg. Humidity (%)	Avg. Temp. (°C)	Avg. CO2 (ppm)
Hus 1 A/B - Afd			169/168	178/32	669/640	13.5	3.5	2462	1289	87	21.1	743
Hus 2 - Afd			168/168	245/32	882/640	103.5	4.6	724	2661	74	21	714
Hus 3 - Afd			165/168	232/32	788/32	0	4.1	[illegible] Last day value: 4364	[illegible]	[illegible]	20.6	530
Hus 4 øst/vest - Afd			166/168	233/32	649/32	0	3.4	6919	2468	71	20.7	337
Hus 5 - Afd			162/168	252/32	800/32	0	4.1	0	2884	73	20.3	518
Hus 6 - Afd			157/168	252/32	883/32	0	4.6	2313	2884	73	19.7	638
Hus 7 - Afd			161/168	241/32	903/32	76.5	4.7	1322	2587	73	20.1	758
Hus 8 - Afd			163/168	248/32	865/32	31.5	4.5	754	2733	74	20.4	649
Hus 9 - Afd			163/168	250/32	854/32	0	4.4	3388	2779	75	20.3	540
Hus 10 - Afd			163/168	249/32	815/32	9	4.2	963	2753	85	20.3	536
Hus 11 - Afd			162/168	249/32	878/32	0	4.6	0	2757	77	20.3	681

Figure 3. InfoGrow 2.0 Summary view

With InfoGrow 2.0 the grower gains insights that make it possible to see new perspectives of the plant production:

- Keep an eye on photosynthesis and optimize the climate to optimize the production.
- Know the use of energy for all departments and at a high time resolution without buying expensive sensors.
- Check the greenhouse when deviations from the norm are detected. This could be due to vents or screens in effect under unanticipated circumstances.
- Use the log system customized to specific needs, e.g., documenting the application of biological or chemical pest control
- Compare production time with the weather and time the production even better than today.
- Export data from InfoGrow 2.0™ and use them in Virtual Greenhouse to improve the production even more.

InfoGrow 2.0 has different views designed to help growers to optimize production; Figure 4 shows the Photosynthesis view and Figure 6 shows the Energy view.

Photosynthesis is calculated from a model mainly depending on climatic parameters like temperature, light level, and CO_2 concentration. In the top left part of the view, the current conditions for photosynthesis and climatic parameters are shown. The top right shows the same values but for the selected period of time. The graphs show the photosynthesis sum for the days in the selected period, together with lines for temperature, light and CO2 at plant height. By changing the chart tab, the user can see the photosynthesis together with the CO_2 concentration, temperature, or various information about light (natural light, light screened away, and artificial light, Figure 5). Using this information, the user can optimize the production and benefit as much as possible from the natural light in the greenhouse.

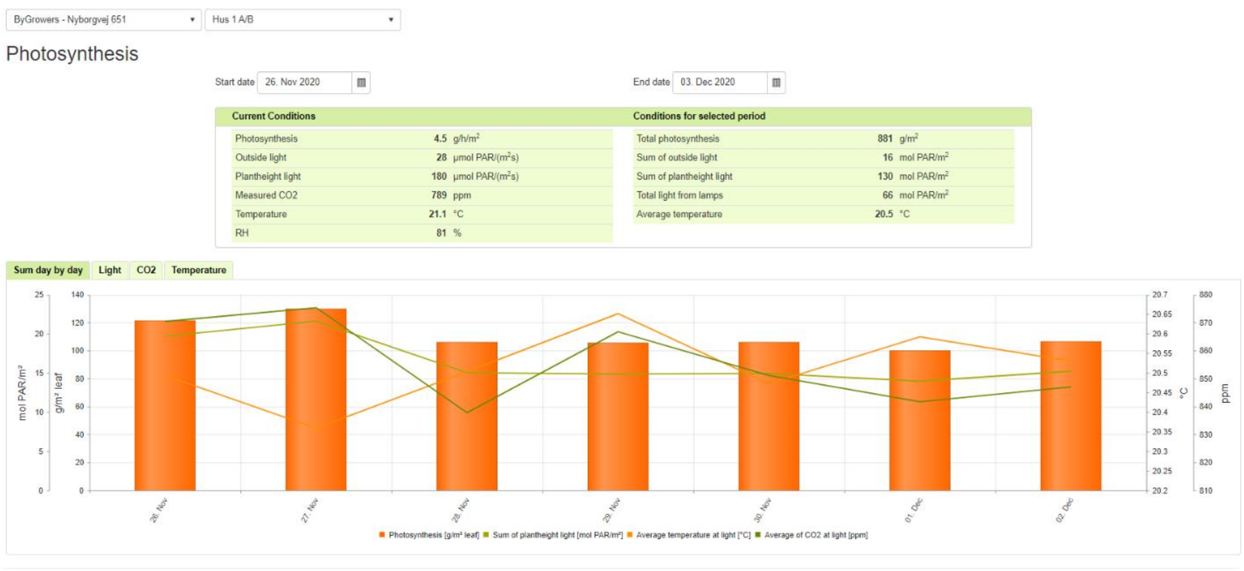


Figure 4. InfoGrow 2.0 screen with information about photosynthesis and climatic parameters.

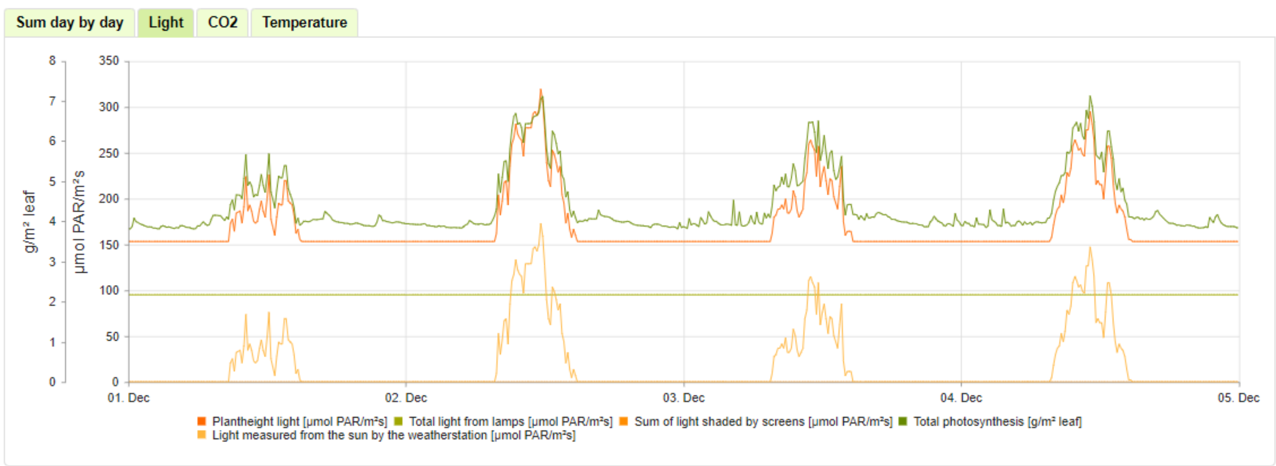


Figure 5. InfoGrow 2.0 Light tab of the photosynthesis view.

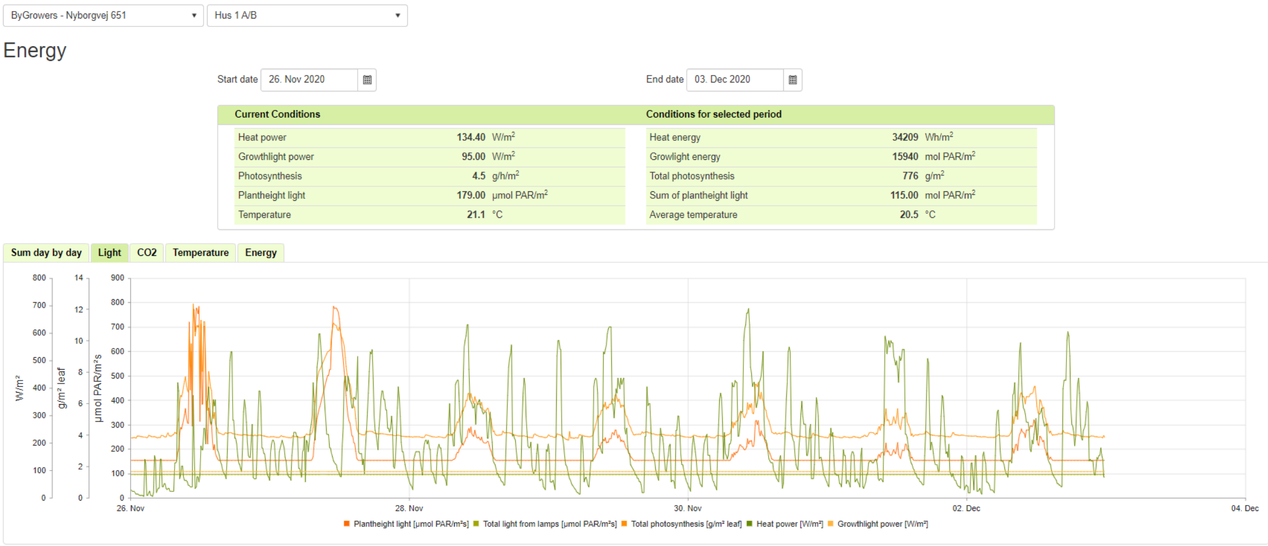
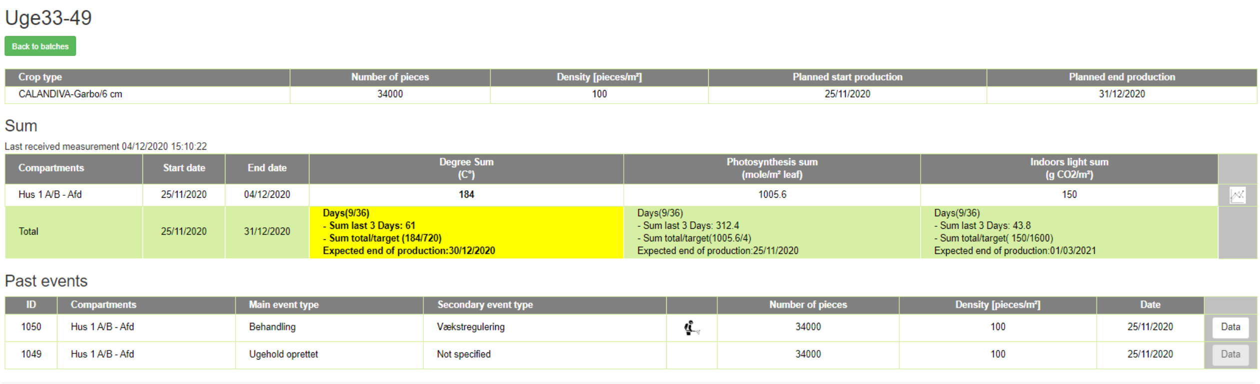


Figure 6. InfoGrow 2.0 screen with information about us of energy and climatic parameters.

The Energy view (Figure 6) presents the modelled use of energy together with the most important climate parameters. The first tab presents the sum of the days as in the Photosynthesis view, while the next tabs show details for the selected days.

For a pot plant producer, it is essential to time the production correctly, as the plants are sold when they are at a specific stage of development. That can, for instance, be when the first flower is fully open, or when it is possible to see the colour of the buds. At the same time, the plants also have to be delivered at a specific date. For a grower who wants to save even more energy than today by using a more dynamic climate strategy, it is essential to know exactly how the plants are influenced by a changed, less energy-demanding climate strategy. Earlier Danish research[3] has demonstrated that a more dynamic climate strategy can save up to 38 % on the use of energy. To make this energy-saving possible, the project started developing a *log system* that can log information about plant development and forecast, when the plants are finished depending on a temperature, light or photosynthesis sum. The system will be further developed in the EUDP funded project Greenhouse Industry 4.0. The user defines a generic log system with different main and secondary logs that can be registered together with user-defined data. This can be data for development, use of pesticides, etc. Figure 7 shows the view of a batch with the planned production day, together with the expected, which depends on the climate obtained during the production.

[3] Aaslyng, J. M., Lund, J. B., Ehler, N., & Rosenqvist, E. (2003). IntelliGrow: A greenhouse component-based climate control system. *Environmental Modelling and Software*, *18*(7), 657–666. https://doi.org/10.1016/S1364-8152(03)00052-5



Uge33-49

Back to batches

Crop type	Number of pieces	Density [pieces/m²]	Planned start production	Planned end production
CALANDIVA-Garbo/6 cm	34000	100	25/11/2020	31/12/2020

Sum

Last received measurement 04/12/2020 15:10:22

Compartments	Start date	End date	Degree Sum (C°)	Photosynthesis sum (mole/m² leaf)	Indoors light sum (g CO2/m²)
Hus 1 A/B - Afd	25/11/2020	04/12/2020	**184**	1005.6	150
Total	25/11/2020	31/12/2020	**Days(9/36) - Sum last 3 Days: 61 - Sum total/target (184/720) Expected end of production:30/12/2020**	Days(9/36) - Sum last 3 Days: 312.4 - Sum total/target(1005.6/4) Expected end of production:25/11/2020	Days(9/36) - Sum last 3 Days: 43.8 - Sum total/target(150/1600) Expected end of production:01/03/2021

Past events

ID	Compartments	Main event type	Secondary event type		Number of pieces	Density [pieces/m²]	Date	
1050	Hus 1 A/B - Afd	Behandling	Vækstregulering		34000	100	25/11/2020	Data
1049	Hus 1 A/B - Afd	Ugehold oprettet	Not specified		34000	100	25/11/2020	Data

Figure 7. InfoGrow view of a batch in the greenhouse production.

4.3 Virtual Greenhouse

Greenhouse technology develops fast, and suppliers keep providing new products claimed to reduce energy consumption. Savings can be achieved by optimizing the climate setpoints, but even larger savings are possible by installing some of the newest equipment. In the Virtual Greenhouse, new installations are simulated, and savings are documented.

It is possible to simulate the greenhouse environment and view the expected effect of different technical innovations, either to optimize the greenhouse construction or to add equipment. such as screens and lighting. The simulations results in a report detailing the effects on energy consumption, plant microclimate and plant production.

Data can also be imported from InfoGrow 2.0 and used to carry out a detailed analysis of the production performance and to test changes that might be implemented. It is even possible to analyse data and find energy hot spots with very high use of energy and test different solutions to avoid them.

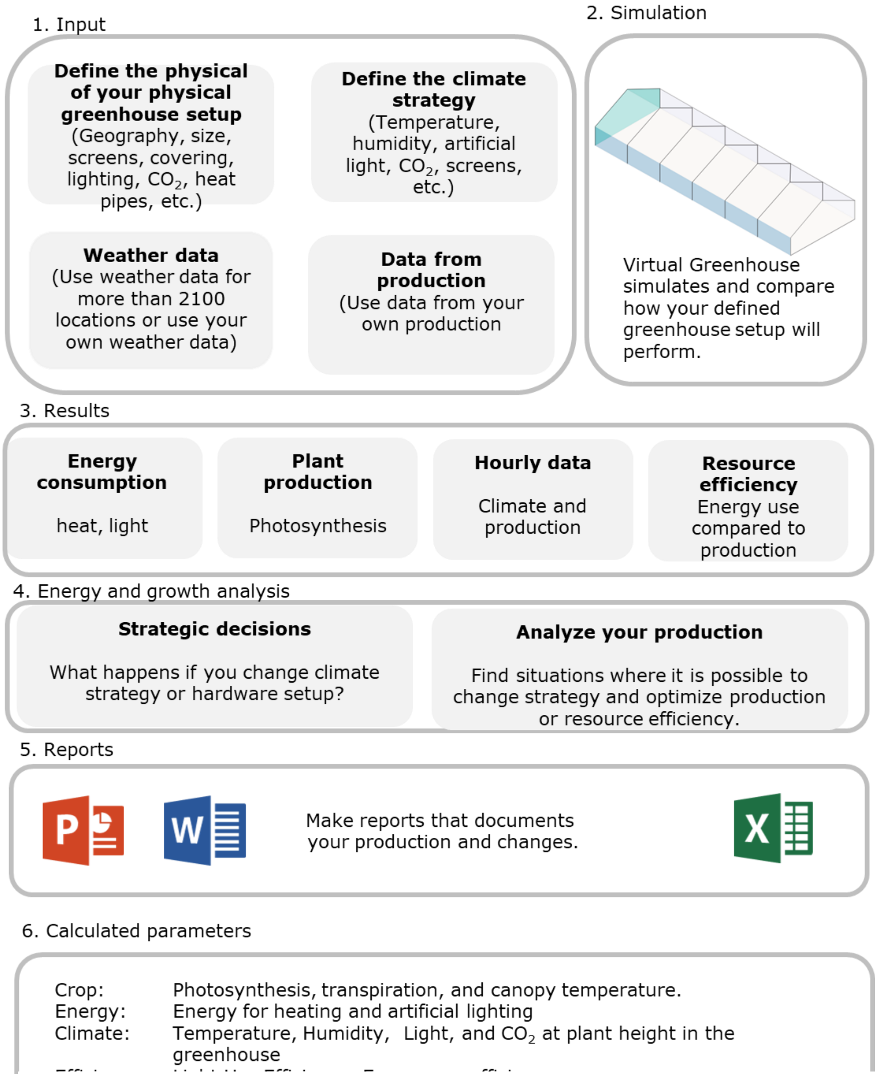


Figure 8. Overview of input and output from Virtual Greenhouse.

Figure 8 has an overview of input and output from Virtual Greenhouse.

4.3.1 Simulation of energy, climate and plant production

After the user has defined the greenhouse structure and the climate control strategy, it is possible to simulate a yearly production. The user can make one or more descriptions and either compare two descriptions or make a sum of several descriptions. It is possible to select outside climate data from almost all over the world through the EnergyPlus[4] web site or data can be used from the weather station of a greenhouse production that are using InfoGrow.

The main result of a simulation is shown in **Error! Reference source not found.**. In the figure, data is presented from a simulation comparing a standard sodium lamp with a modern LED lamp.

Table 1. Main results from Virtual Greenhouse simulation comparing use of LED and traditional sodium light for greenhouse production.

Energy and plant production (absolute values)

Description	Unit	HPS	FL300 Grow 1.1	Difference	Percent
Greenhouse area	m-2	10,000	10,000	0.0	0.0
Total use of energy	MWh Year-1	8,825	7,594	-1,231.0	-13.9
Energy for heating	MWh Year-1	2,204	2,843	639.0	29.0
Energy for artificial light	MWh Year-1	6,621	4,751	-1,870.0	-28.2
Crop growth (Net Photosynthesis)	g m-2	7,710	7,762	52.0	0.7
Light Use Efficency	mg CO2 J-1	0.003	0.003	0.0	0.0
Total energy used to produce 1 kg dry plant material	MW kg-1	412.1	352.2	-59.9	-14.5
Heating energy used to produce 1 kg dry plant material	MW kg-1	102.9	131.8	28.9	28.1
Light energy used to produce 1 kg dry plant material	MW kg-1	309.2	220.4	-88.8	-28.7
Heating energy, cost	Euro	66,112	85,278	19,166.0	29.0
Light energy, cost	Euro	397,254	285,088	-112,166.0	-28.2
Total energy, cost	Euro	463,367	370,367	-93,000.0	-20.1

Table 1 shows that when using a LED lamp, the grower can save 28.2 % of the yearly use of electricity but also use 29.0 % more energy for heating. In total, 13.9 % of energy was saved when changing from traditional sodium lamps to LED lamps with a minor increase in photosynthesis. The table also shows that there is used 14.5 % less energy to produce 1 kg of plant material. In Figure 9 one of the many figures that are made by the Virtual Greenhouse is shown. The figure shows the light use efficiency for tradition and LED lighting throughout the year.

[4] https://energyplus.net/weather

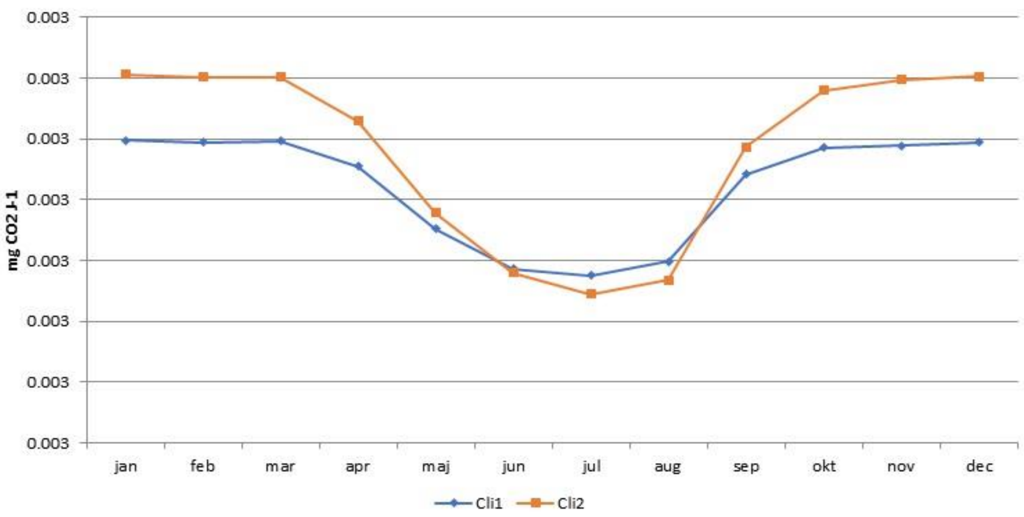


Figure 9. Light use efficiency when using LED (FL300 Grow 1.1) og traditional sodium light. (HPS)

UniSim and the Virtual Greenhouse calculate more than 70 different parameters describing the status of greenhouse production. An overview of the different type of parameters are shown in Table 2

Table 2. Overview of parameters calculated by UniSim and used by Virtual Greenhouse.

Status of the climate control strategy	Positions of vents, positions of screens, use of CO2, etc.
Climate outside the greenhouse	Temperature, humidity, wind flow, irradiance
Climate in the greenhouse	Irradiance, temperature, CO2 concentration, humidity
Climate in the plant canopy	Leaf temperature, humidity, irradiance
Setpoints	Current setpoints for temperature, humidity, lighting etc.
Plant production	Leaf photosynthesis, transpiration
Energy	Energy for heating and artificial light
Efficiencies	Light use efficiency, heat use efficiency.

Virtual Greenhouse can automatically generate different kinds of reports from the simulation (Figure 10). The simulation creates a report describing energy expenditures, plant climate and plant production in detail. An example report is attached in appendix 1.

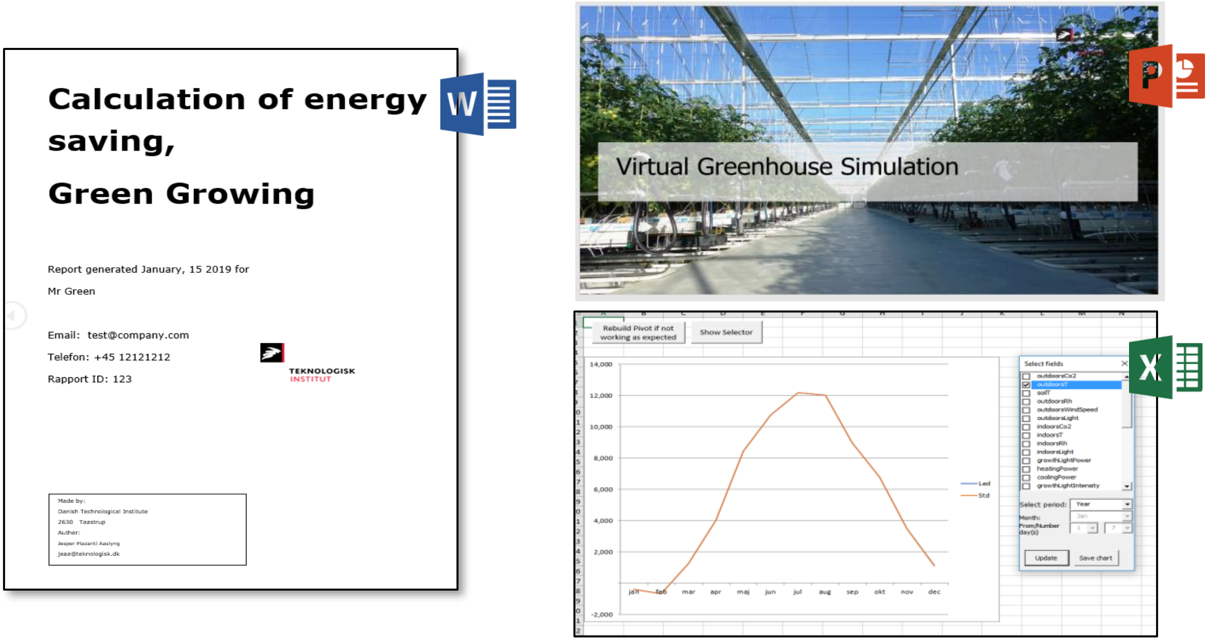


Figure 10. Different reports from Virtual Greenhouse. Automatically generated Word or PowerPoint report or manual generated reports from excel using Pivot tables.

4.3.2 Analysis of climate and use of energy

After the user has run a simulation or imported real greenhouse data from InfoGrow, the Virtual Greenhouse has data for year-round greenhouse production. With these data, Virtual Greenhouse has facilities to analyse the climate for different critical situations. This can be high use of energy, risk of diseases, low production, or low energy use efficiencies.

Figure 11 shows the daily use of energy plotted against the difference in temperature between in and outside together with a regression line that can be compared from year to year to indicate, if the grower is utilizing the energy better from year to year.

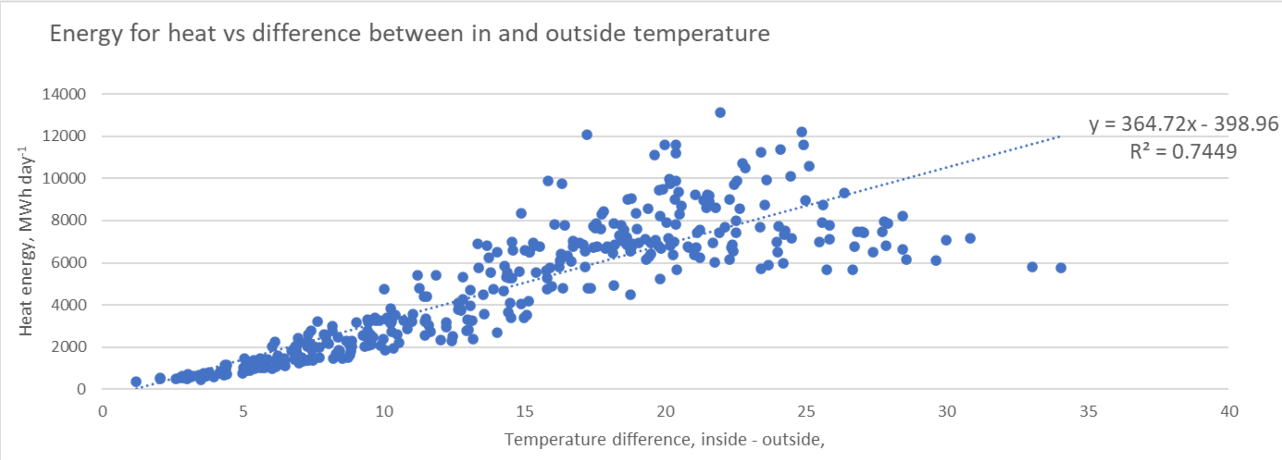


Figure 11. Daily use of energy plotted against the difference in outside and inside temperature.

Together with the figure, a table is generated with a list of the days with the highest use of energy (Table 3). The list includes the weather conditions of the day and the day's percentage of the yearly use. From this list, the grower can consider how to change the climate control strategies on the days with the highest use of energy.

Table 3. List of days that use most energy for heating

Date	Energy, Heating	Pct of yearly use	Temperature difference	Outside temperature	Greenhouse temperature	Wind speed	Outside light	Daily use of screen	RegressionHeat
16-jan	13,129	0.7	21.9	0.5	22.4	8.0	38.3	16.87	7,603
17-jan	12,184	0.7	24.8	-2.1	22.7	2.9	25.4	16.69	8,659
01-jan	12,079	0.7	17.2	4.6	21.8	13.4	8.7	16.81	5,882
02-jan	11,610	0.7	20.0	3.2	23.2	7.3	21.8	18.15	6,886
08-feb	11,605	0.7	24.9	-2.8	22.1	2.6	56.8	17.32	8,691
09-jan	11,596	0.7	20.4	2.9	23.3	7.1	4.8	17.49	7,037
27-jan	11,368	0.6	24.1	-1.2	22.9	2.6	39.8	14.78	8,381
26-jan	11,244	0.6	23.4	-0.8	22.6	4.5	53.1	17.67	8,132
10-apr	11,213	0.6	20.4	2.5	22.9	7.4	58.2	17.17	7,036
25-mar	11,095	0.6	19.6	3.0	22.6	11.2	56.1	16.66	6,753
10-jan	10,708	0.6	22.7	0.6	23.3	2.9	18.5	17.21	7,889
13-jan	10,566	0.6	25.1	-3.2	22.0	1.5	34.5	14.96	8,760
11-jan	10,484	0.6	22.8	-0.8	22.0	2.4	32.3	17.16	7,926
30-dec	10,115	0.6	24.4	-1.6	22.9	2.7	29.6	17.20	8,512
04-jan	9,975	0.6	20.1	0.7	20.9	4.7	5.8	18.22	6,945
09-feb	9,908	0.6	23.6	0.1	23.7	2.0	11.4	16.64	8,209
03-mar	9,887	0.6	20.4	2.6	23.0	4.0	13.8	16.22	7,034
02-feb	9,865	0.6	22.5	-0.6	21.9	4.6	33.3	16.47	7,822
03-dec	9,864	0.6	15.8	7.5	23.4	9.4	10.5	16.08	5,379
03-jan	9,768	0.6	20.2	2.7	22.8	4.1	3.7	16.54	6,955

Another Virtual Greenhouse facility is to analyse different critical situations and how they influence use of energy and production. Table 4 shows that 122 hours (5 days) with a wind speed at more than 6 m s^{-1} used 3.4 % of the yearly use of energy. The grower can then consider changing the climate control strategy (lowering the temperature or more use of screens) in these special situations.

Table 4. Analysis of situations with high wind speed, low temperatures, and low light level (night) and the corresponding use of energy and the percentage of the yearly use of energy.

outdoorsWindSpeed m s-1	outdoorsLight Wm-2	outdoorsT °C	Hours number	Photosynthesis g CO2 m-2	Heating MWh	Light MWh	Photo %	Heat %	Light %	Cost, Heat
11	5	5	0	0.00	0	0		0.0		0
10	5	5	1	0.00	3	0		0.0		91
9	5	5	4	0.00	40	0		0.0		1,204
8	5	5	11	0.00	254	0		0.2		7,626
7	5	5	51	0.00	1,153	0		0.8		34,598
6	5	5	122	0.00	3,435	0		2.3		103,060
4	5	5	420	0.00	11,255	0		7.4		337,639
3	5	5	646	0.00	16,805	0		11.1		504,145
2	5	5	808	0.00	21,327	0		14.0		639,823
1	5	5	914	0.00	24,496	0		16.1		734,884

The hour-based analysis can be used to search for many different situations that are important for both the use of energy and plant production. Examples are the use of artificial light with very low plant production, or very high humidity that gives a risk for diseases in the plants.

4.4 Research as background for InfoGrow and Virtual Greenhouse

4.4.1 Light transmission

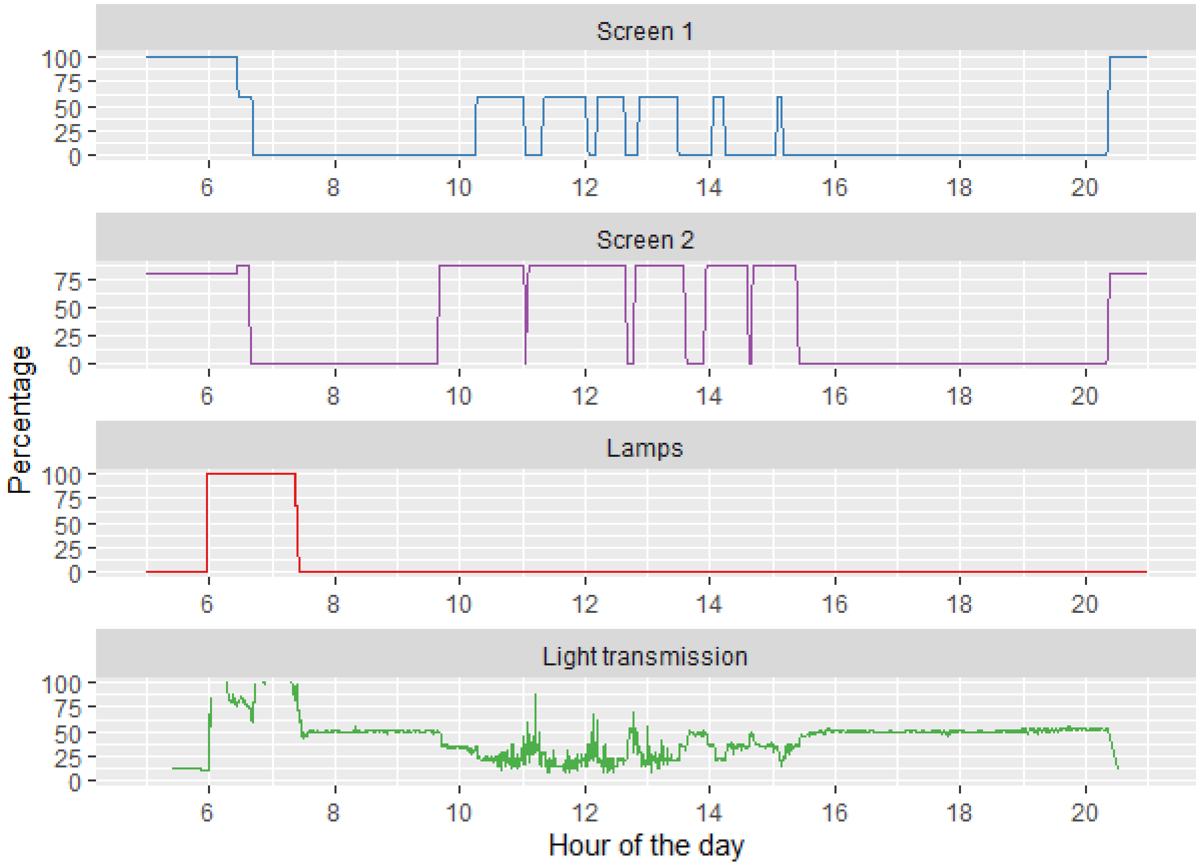


Figure 12. Light transmission measured on 17 May 2020 in a greenhouse at Hjortebjerg nursery shown together with logged state of screens and lamps.

The intensity of light was measured continuously outside and inside a greenhouse over several days in May 2020 at Hjortebjerg nursery, using reference PAR meters (LI-COR 191 Line Quantum Sensor). Light transmission (%), computed as the indoors/outdoors ratio of light intensity, was compared to the concurrent settings of greenhouse screens (numbered 1 and 2) and lamps (one group), logged by the greenhouse computer. A typical day is seen in Fig. 12. Screens were drawn from 20:30 to 6:30 to save energy and intermittently during the day to provide shade. Lamps were on 6:00 to 7:30. The response in light transmission is seen 6:00-7:30 when it was larger than 100% due to the lamps. During periods without screening, the light transmission was *c*. 50% while shading brought it down to *c*. 15%.

These results show that it is possible to calculate indoors light intensity from the outdoors. However, the experiment highlighted several factors that are likely to add uncertainty to this calculation. These uncertain concerns outdoors light (Is the nursery climate station properly calibrated?), the position of the screens (Are screen positions logged truthfully by the greenhouse computer?), the physical characteristics of the screens (Are screen producers willing to provide parameters for light reflection, transmission, etc.?). On top of these uncertainties come others, which are more easily fixed but not without an effort: Is the glass currently whitened? What is the basic light transmission into the greenhouse when unscreened (This depends on characteristics specific to the greenhouse type, mostly shading caused by frames and technical installations).

In comparison to the complexities of calculating incoming sunlight, the light provided by the lamps are well specified, albeit their output will degrade with time. In any case, lamp outputs are easily measured with a handheld light meter.

In conclusion, it is possible to simulate indoors light in the Virtual Greenhouse given assumptions about (i) the basic light transmission into the greenhouse and (ii) the physical characteristics of the screens. For InfoGrow, the same assumptions (i-ii) apply but, since the objective is to estimate indoors light based on current readings of outdoors light and the position of screens, the estimate will be surrounded by much uncertainty. The most reliable measure of indoors light will thus be by way of indoors light sensors. These are not expensive; the main obstacle is to implement a flexible integration with other sensors logged by the greenhouse computer. The uncertainty regarding the quality of the nursery weather station could possibly be alleviated, if precise sunlight estimates could be obtained from an online weather service.

4.4.2 Wireless light sensors

Wireless sensors (two from SiGrow and four from 30-MHz) were installed indoors, together with the reference PAR meter, to test their quality and possibly derive calibration parameters to convert their readings into precise PAR estimates. The results show that both sensors could be calibrated to give precise estimates of indoors PAR intensity (Figs. 13 and 14). The estimates of the calibration factors are preliminary; they will be corrected as soon as the reference sensors have undergone a high-precision calibration themselves. The noise on the calibration factor was likely caused by wandering shadows created by the greenhouse construction.

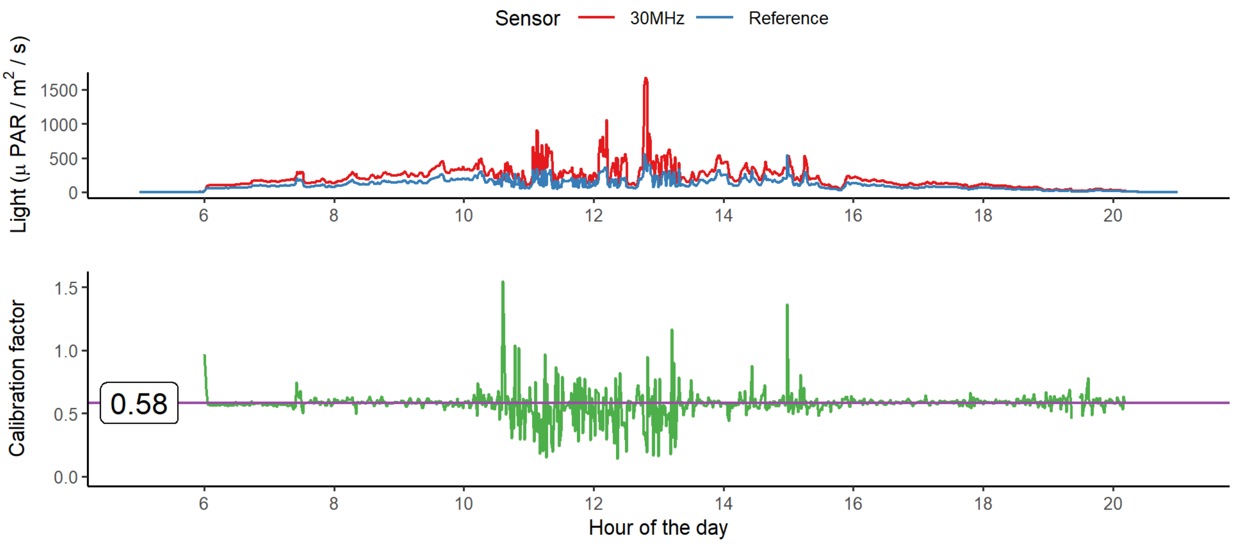


Figure 13. Light intensity measured on 17 May 2020 in a greenhouse at Hjortebjerg nursery. Average readings from four 30 Mhz sensors were divided by those of a reference sensor to obtain the calibration factor 0.58.

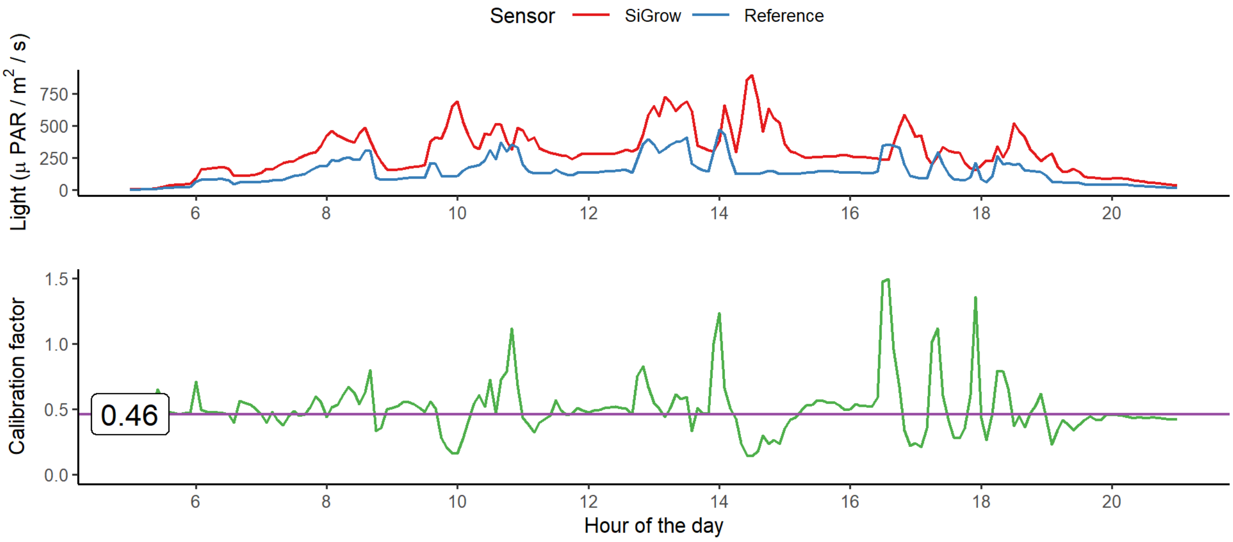


Figure 14. Light intensity measured on 28 May 2020 in a greenhouse at Hjortebjerg nursery. Average readings from two SiGrow sensors were divided by those of a reference sensor to obtain the calibration factor 0.46.

4.4.3 Heat pipe energetics

At Hjortebjerg nursery, the main and secondary heat pipes of three greenhouses were equipped with Fluxus F601 ultrasonic clamp-on flow meters. The meters logged the water temperature both at the inlet and the outlet every 10 minutes or less. The data set is comprised of these time series:

- Greenhouse 1: 15 May 20-23 Sep 20
- Greenhouse 2: **17 Apr 18-8 Aug 18**, 2 Oct 19-23 Feb 20, 15 May 20-4 Sep 20
- Greenhouse 3: 20 Feb 20-29 Mar 20, 15 May 20-30 July 20

A mathematical model was derived to predict the temperature at the outlet from that at the inlet. The model parameters were estimated from the first time series from Greenhouse 2 (in bold above) by non-linear regression. The other time series are currently being analysed to validate the model and a scientific paper presenting the whole analysis is in preparation. Here, we will present only the results from the analysis based in the first time series.

This following heat pipe equation was derived from first principles:

$$T_{out}(t) = T_{air}(t) + [kd(b-1) + \{T_{in}(t-\Delta t) - T_{air}(t)\}^{1-b}]^{\frac{1}{1-b}}$$

$T_{in}(t)$: pipe temperature at the inlet at time t

$T_{out}(t)$: pipe temperature at the outlet at time t

$T_{air}(t)$: greenhouse air temperature at time t

Δt: the transit time of water from inlet to outlet

d: the inner diameter of the pipe (mm)

k and b: regression coefficients

The behaviour of the heat pipe equation can be studied in Fig. 15. The model gave predictions precise enough (Fig. 16) to be useful, both to calculate current energy expenditure in InfoGrow and to simulate the energy budget in the Virtual Greenhouse.

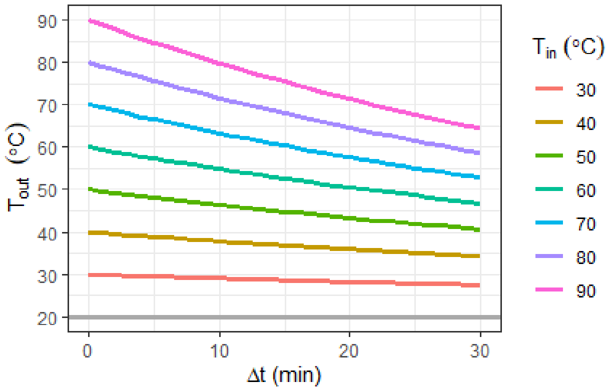


Figure 15. Pipe temperature at the outlet (T_{out}) falling with increasing transit time (Δt), predicted by the heat pipe equation at different inlet temperatures (T_{in}) with a greenhouse temperature of 20 °C.

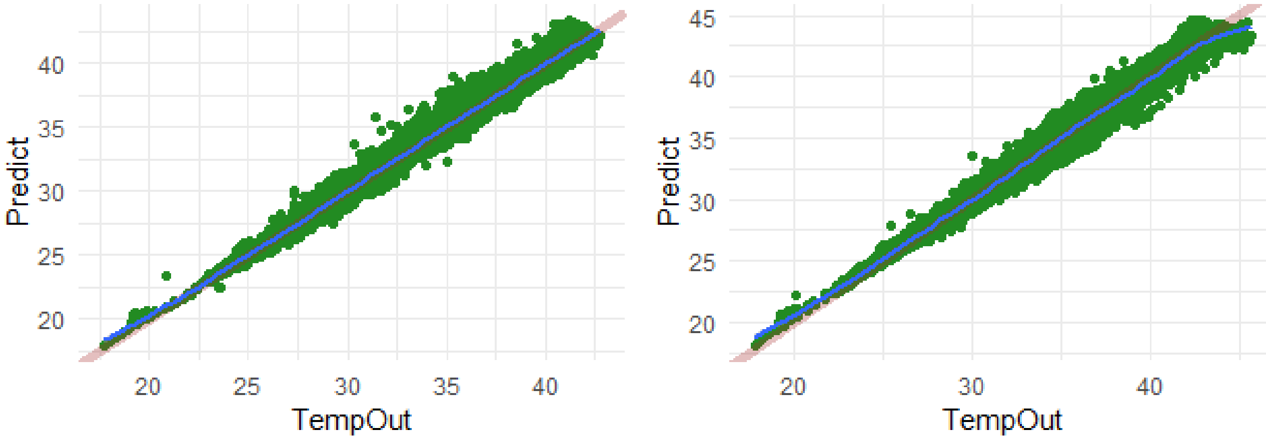


Figure 16. The performance of the heat pipe equation. Measured outlet temperature (*TempOut)* compared to the outlet temperature predicted by the model (*Predict*). The diagonal line shows the ideal 1:1 relation.

4.4.4 Plant growth and Humidity

Greenhouses are high energy-consuming facilities. Since the early 2000s, energy use was reduced with the introduction of crop directed climate control regimes with dynamic temperature boundaries. Increasing greenhouse insulation (i.e., semi-closed and closed greenhouse systems) further reduced energy use required for heating, however, temperature and relative air humidity (RH) control remain the two main challenges in these concepts. Potential risks with accidental increase of RH above 85% are increased incidence of fungal diseases (e.g., powdery mildew and botrytis) and induction of physiological disorders and in the long term, the development of stomata with reduced closing ability. Although the occurrence of malfunctional stomata remains undetected during cultivation, it becomes apparent when plants rapidly wilt upon exposure to lower RH such as during sales. However, the objective of keeping RH below 85% is counteracting the striving for low energy consumption. The energy needed for dehumidification (by heating) increases when RH is adjusted to lower levels. Despite great efforts devoted to the development of more efficient dehumidification methods, reducing RH to a safe level (≤ 85%) remains rather costly, accounting for over 20% of annual energy consumption in Northern European climates. As such, improved RH control will lead to a major decrease in both energy demand and CO2 footprint, combined with a better (visual and inner) quality of the produce. The crop itself is a major driver for RH via crop evapotranspiration (ETc), thus its accurate estimation is essential for greenhouse climate control.

An initial literature study focused on the "effect of humidity on energy consumption" in combination with an internal workshop, opened up the discussion of how we can develop tools to monitor and study the subject further. Initial visits to the participating nurseries (Hjortebjerg and ByGrowers) and discussions about their specific challenges in relation to humidity as well as production planning formed the basis for experiments in climate chambers.

Climate and production data from the two nurseries were analysed. The two nurseries are very different in their challenges. With regard to Hjortebjerg, we focused on the periods when energy consumption was high due to natural ventilation and analysed the diversity between the three main production units. The increased ventilation reflects specific settings in the climate computer, but it is unclear whether the setpoints for ventilation are set to avoid humidity problems, grey mould, "stagnant air" or other things. We investigated how *Euphorbia milii* responds to high, medium and low levels of relative humidity (RH) and water status to clarify, whether the settings in the climate computer are optimal, or whether we can define more energy efficient setpoints that will result in less ventilation. In the period from July to spring 2019, we focused on experimental studies of the response of *Euphorbia milii* to both different humidity conditions and reduced water supply, to address the problems presented in the nursery with reduced quality and unusual energy requiring repeated ventilation. The climate data analysed from the main compartments reflected very different strategies; in one compartment there were many ventilation episodes that reduced CO_2 level and increased energy costs.

The plan for further experiments (some general light/temperature/VPD measurements and different CO_2 levels to improve the model performance) was delayed due to relocation of the department to a new site in Skejby and was cancelled due to the pandemic, as we were not allowed to run experiments, and some of the needed facilities (climate chambers) were delayed.

In the summer 2020, an experiment was carried out with two varieties of *Kalanchoë* which were grown at different RH and with higher temperature setpoints and higher CO_2 levels. The idea was to assess whether higher humidity result in a lower leaf temperature and thus the possibility of increasing photosynthesis by elevated CO_2. The results indicated that under late summer conditions increasing the temperature setpoint for ventilation allowed for a higher CO_2 concentration in the greenhouse and increasing the biomass production even in

Kalanchoe which in the flowering phase is very slow growing. The results show that higher humidity is not causing problems provided that the humidification is not extended too long in the afternoon. The active use of humidification can actually result in an energy saving since more energy from the sun is used. The results will subsequently be incorporated into InfoGrow 2.0.

4.4.5 Energy savings through changes in humidity control

As reported earlier, (Fanourakis, Giday, et al., 2019) adjusted RH based climate control can strongly reduce energy consumption in greenhouses, while implementing RH related algorithms in a greenhouse climate controller especially in modern highly insulated greenhouses is the preferred choice. We have developed the basis for a cultivar-specific, model-based climate control system (scientific paper submitted). Simulations have shown that the system is robust for estimating ETc over diverse different pot rose cultivars and environmental conditions. The satisfactory agreement between actual data and estimated values indicated the strengths of the model as a framework and the reference for validating other approaches of calculating stomatal conductance (g_s). For energy saving and crop-based climate control, crop and cultivar specific parameterisation of the underlying models is important. Large differences in ETc (>20%) were noted among cultivars, which together with environmentally induced variation resulted in a wide ETc range. This range was used to adapt and extend the BWB-Liu-model, parameterize, calibrate, and validate the underlying parameters and finally implement it in a greenhouse simulator.

The modified g_s model improved g_s estimation (r^2 of 0.59 *vs*. 0.31) (Körner et al submitted). A very good agreement between simulated and measured ETc was achieved. Depending on the RH set point, selecting low-transpiring cultivars may save between 2.5% and 5.8% of energy consumption on an annual basis. Incorporating the presented cultivar specific model in decision support tools and climate control will enable model-based controllers to adjust climate more efficiently (with real-time decision support systems) and create ground for planning tools in greenhouse construction (in association with greenhouse planning tools such as Virtual Greenhouse and InfoGrow 2.0).

In 2017, MSc student Michael Hwang wrote a MSc thesis on “Impact of reduced humidity on growth and stomatal conductance modelling in potted roses (*Rosa hybrida* L.) in two plant densities”. The much used Ball model of stomatal conductance (Ball 1987[5]) have been

[5] Ball, J.T., I.E. Woodrow and J.A. Berry.1987. A Model Predicting Stomatal Conductance and its Contribution to the Control of Photosynthesis under Different Environmental Conditions. Progress in Photosynthesis Research. Martinus Nijhoff Publishers, The Netherlands.

improved by Liu (Liu *et al*., 2008[6]) by including the soil water status in the model. This model was further improved drastically by including stomatal properties in the model. The properties in question was either stomata pore aperture or stomata density. The first requires laborious microscopy, while the latter can be scanned with a portable micro scanner connected to a laptop, and counted automatically by custom designed image analysis software. Since the stomata density only changes over seasons it is an input that could be feasible to use in a greenhouse setup. The improved model is included in Körner *et al*. (submitted 2020).

4.4.6 Thermovision as a tool for greenhouse industry

In the period from July to spring 2019, we focused on experimental studies of the response of *Euphorbia milii* to both different humidity conditions, and reduced water supply, to address the problems presented in the nursery with reduced quality and unusual energy requiring repeated ventilation.

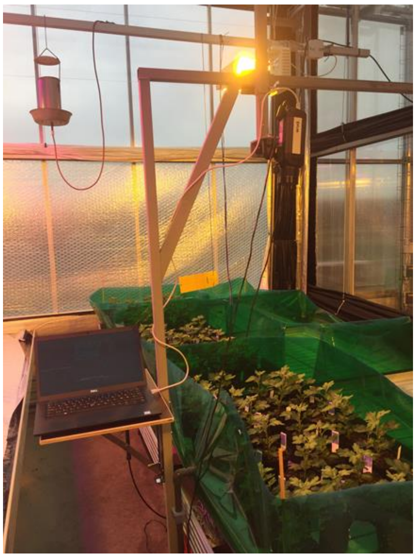


Figure 17. Experimental set up at Højbakkegaard

We have conducted two experiments using the drought spotter with different humidity levels (60% or 80% relative humidity (RH)) and 80% water supply, demonstrating the effects of fluctuations in humidity on the stomatal conductance using continuous gas exchange measurements, but the results are not very conclusive. One challenge was that the plants have a very slow gas exchange rate and subsequent transpiration, so the reduced water treatment took more than a week to obtain. Preliminary data showed that the reduced water supply affected the gas exchange to a small degree, but the plants were less sensitive to high RH. One of the challenges is, however, that the irrigation (which did not happen every day due to low transpiration) obviously changes the microclimate. The results demonstrated that low humidity and reduced watering seemed to have a negative effect on photosynthesis, and that the well-watered plants propagated in high humidity conditions had the best growth. Unfortunately, this does not leave much room for energy savings based on reducing the humidity and watering. The gas exchange studies were challenged by the very low capacity for photosynthesis, even though the link between gas exchange and stomatal conductance was as expected. Potentially, large flowering plants are reducing their gas exchange during flowering, so the remaining studies could be a repetition of the previous just using young plants and small adjustments to the climate. Alternatively, we could perform some general

[6] Liu, F., R. Song, X. Zhang, A. Shahnazari, M.N. Andersen, F. Plauborg, S.V. Jacobsen and C.R. Jensen. 2008. Measurement and Modellingof ABA Signalling in Potato (*Solanum tuberosum*L.) during Partial Root-Zone Drying. Environ. Exp. Bot. 63:385-391.

light/temperature/VPD measurements and different CO_2 levels to improve the model performance.

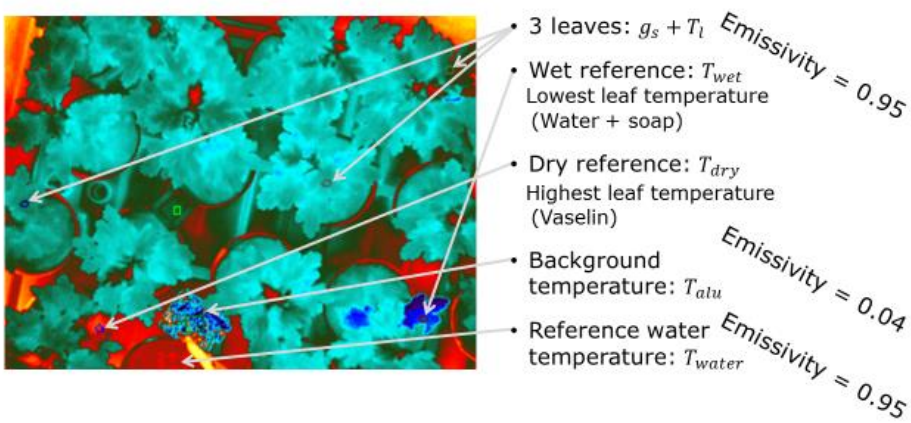


Figure 18. Overview of the different measurements made in the study of thermal imaging.

We have combined thermographs with stomatal conductance and transpiration in experiments with weighing tables. The work on establishing reliable measuring protocols for the thermal camera has continued. In November 2018 MSc student Baptiste Mussotti (BM) was linked to the project for nine months. His topic is “The variation in the leaf temperature related to the transpiration rate of the plant”, where he uses thermography to quantify the variation in canopy temperature and transpiration, in addition to the work done by permanent staff in the project. Thermography gives very precise (better than 0.1°C resolution) temperature measurements *within* a picture, while the accuracy *between* pictures can vary within a couple of degrees because the thermographic measurement is dependent on the temperature of the thermal camera itself. It is only in very expensive temperature-controlled cameras (often cooled with liquid nitrogen) that this can be avoided. BM has made a series of detailed technical experiments to evaluate how different “internal standards” for temperature can be included in the picture to make it possible to compare images taken different days. He has developed measuring protocols for the thermal camera in relation to stomatal regulation and transpiration. In the first plant experiment with *Chrysanthemum* in February–March, a fairly weak correlation was found between stomatal conductance and leaf cooling when grown under high and low air humidity. The stomatal conductance was high in both treatments on all measuring days giving a narrow range of data, which explains the weak correlation. Late winter and early spring is when it is easiest to keep constant non-stressful climate conditions in the greenhouse. In June–July a new experiment is being done where some plants will be stressed by decreasing the water availability, also including some drought cycles to trigger stomatal closure to provide a data set with a wider range of data for analysis. The continuation of these experiments will be decided based on the results from the ongoing experiment and after discussions with the other project partners.

Furthermore, a transpiration model has been written into the statistical program “R”, and tested on the *Euphorbia* results from 2.1, though showing that it was very hard to fit the model as the transpiration and stomatal conductance of Euphorbia was very low in the current experiment. There have been discussions among growers about how a photosynthesis model based one species can be used for other species. To address this question, light and CO_2 response curves have been measured, until now on *Rosa x hybrida*, *Euphorbia milii*, *Chrysanthemum morifolium, Hibiscus rosa-sinensis, Kalanchoe blossfeldiana* (C_3 state) and *Spathiphyllum wallisii*. The data will form the basis for a validation of the photosynthetic model in the coming period. The results will also be processed into a paper for Gartner-Tidende.

4.5 Photosynthesis – driving the climate control strategy

To summarize some of the observations done in the new diversified input data set for the photosynthesis model from seven species, a few figures with main conclusions are presented here, mostly related to the general shape of the curves and to the stomatal conductance.

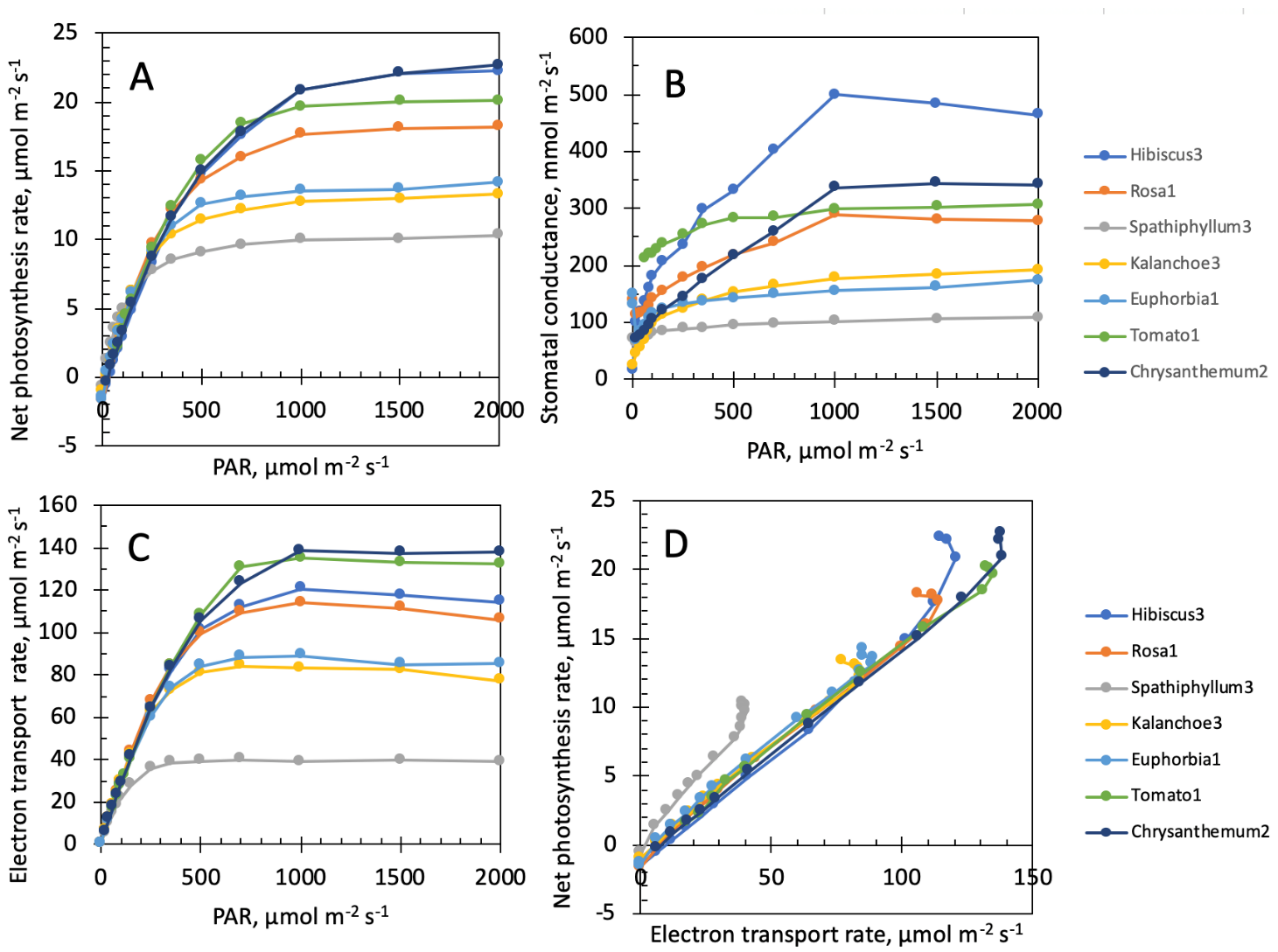


Figure 19. The light response curve of randomly selected individuals of seven species. The light response of photosynthesis (A), stomatal conductance (B) and electron transport (C), and the dependence of CO_2 fixation (net photosynthesis rate) on electron transport.

The rate of photosynthesis differs between species but there are several features that are the same (Figure 19). All species follow the same general shape of a non-rectangular hyperbola but the light saturated rate of photosynthesis differs between the species (Figure 19 A). Some species are obligate low light plants like *Spathiphyllum*, while others are high light species like *Chrysanthemum*, *Hibiscus*, *Rosa* and Tomato. The more high-light adapted the plant is, the higher light level is needed for the plant to reach light saturation. However, the maximum quantum yield (*i.e*. the maximum slope of the light response curve at low light) is the same in all species (Figure 19 A). It means that the climate control at low light in a winter situation at PAR ≤ 500 µmol m^{-2} s^{-1} does not need to differ between species except in extreme shade species like *Spathiphyllum,* where light saturation is about to be reaches already at that modest light level. This is a very positive result because this is the time of the year when energy savings are most needed. The results indicate that a joint climate control strategy can be used in relation to the light level and only different known differences in temperature requirement for the different species has to be applied.

Overall, the photosynthesis level at light saturation differs between the species but it is also related to the light level where it is reached. Therefore, from a climate control point of view it is enough to establish at which light level e.g. 90% of light saturation is reached.

The plants adjust the stomatal conductance (g_s) according to their need i.e. low light plants have lower g_s than high light plants (Figure 19 B). All plants also lower g_s at low light. Under some conditions, plants can have excess g_s in comparison to what is needed for the supply of CO_2 to the leaf, which is seen in the *Hibiscus* curve above.

In the photosynthesis models both parameters related to the carboxylation efficiency in the Calvin-Benson cycle (V_{cmax}) and electron transport (J_{max}) are included. The light response of electron transport (Figure 19 C) follows a similar pattern as the light response of CO_2 assimilation (Figure 19 A). A plot of net photosynthesis rate versus electron transport rate (Figure 19 D) illustrate that the two processes follow each other under most light level except at the highest rates of photosynthesis *i.e.* at light saturation, where the relationship deviates from a linear response. Also here, the low light *Spathiphyllum* deviates, but this species belongs to a minority of species grown in Denmark. Most grown species are high light species.

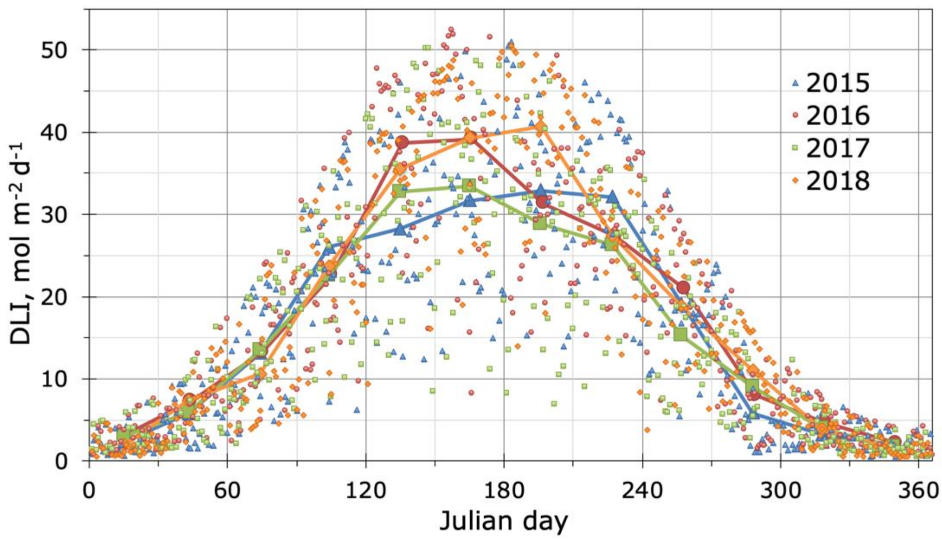


Figure 20. The daily light integral (DLI i.e. light sum) at University of Copenhagen in Taastrup during four years. The single dots are for each day and the connected dots are mean values per month.

Except for extreme low light plants like *Spathiphyllum*, most plants acclimate to the prevailing light level where it grows. It means that the light repose of photosynthesis will differ between summer and winter season because the daily light integral varies by a factor 10 between summer and winter (Figure 20).

Chrysanthemum is a good example of a species that acclimates well to the prevailing light conditions, which means that they have the ability to lower their rate of photosynthesis when growing at low light (Figure 21 A). The consequence is that both the CO_2 fixation and electron transport is down-regulated in low light plants. It is a cost-benefit response of the plant since lower light levels can only support a “small photosynthetic machinery” i.e. low concentrations of the enzymes involved in photosynthesis. Numerous stoichiometric changes happens in the photosynthetic components but a change in leaf morphology also contribute strongly to the light acclimation, where leaves growing in low light are considerably thinner that those grown at high light (Figure 22). However, when comparing photosynthesis curves like this, the stomatal conductance affects the results. Values ≤ 200 mmol m^{-2} s^{-1} induce a stomatal limitation of photosynthesis. Therefore, one can expect that photosynthesis in low light *Chrysanthemum* may be slightly higher than what was measured here, if the stomatal conductance had been higher.

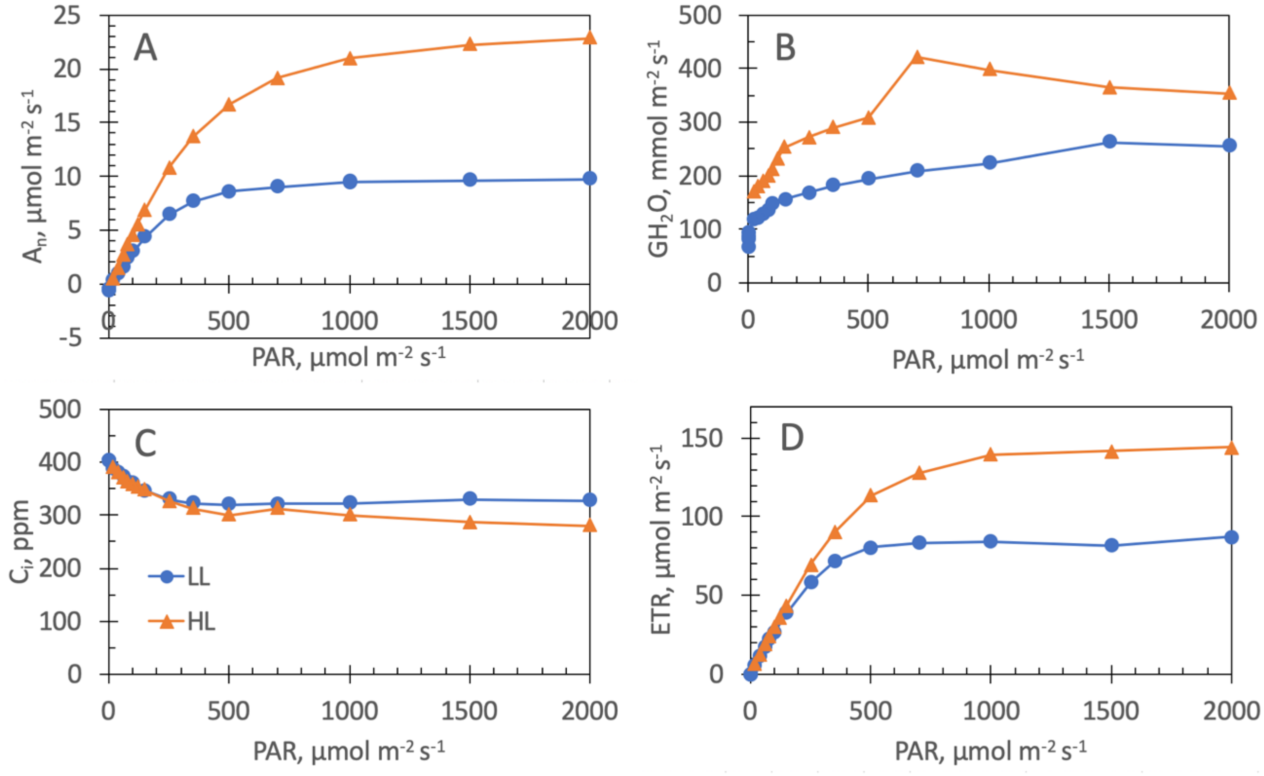


Figure 21. Light response curves of Chrysanthemum that has be growing in high and low light to simulate different growing seasons. The light response of (A) net photosynthesis, (An for net assimilation of CO_2), (B) stomatal conductance (GH2O), (C) intracellular CO_2

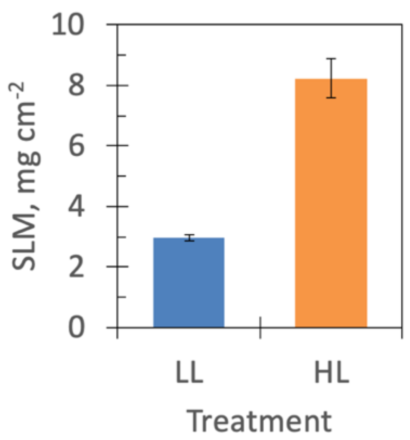


Figure 22. The specific leaf mass i.e. leaf thickness of Chrysanthemum leaves grown in low light and high light (see Figure 21).

In greenhouse production in Denmark almost all nurseries work with elevated CO_2. We have CO_2 response curves for the species mentioned, but would like to show one example of measurements of light response curves on Chrysanthemum grown at 400 and 800 ppm CO_2 and measured at respective CO_2 concentration. This data set clearly illustrates the importance of creating a climate where the plants have a good stomatal conductance.

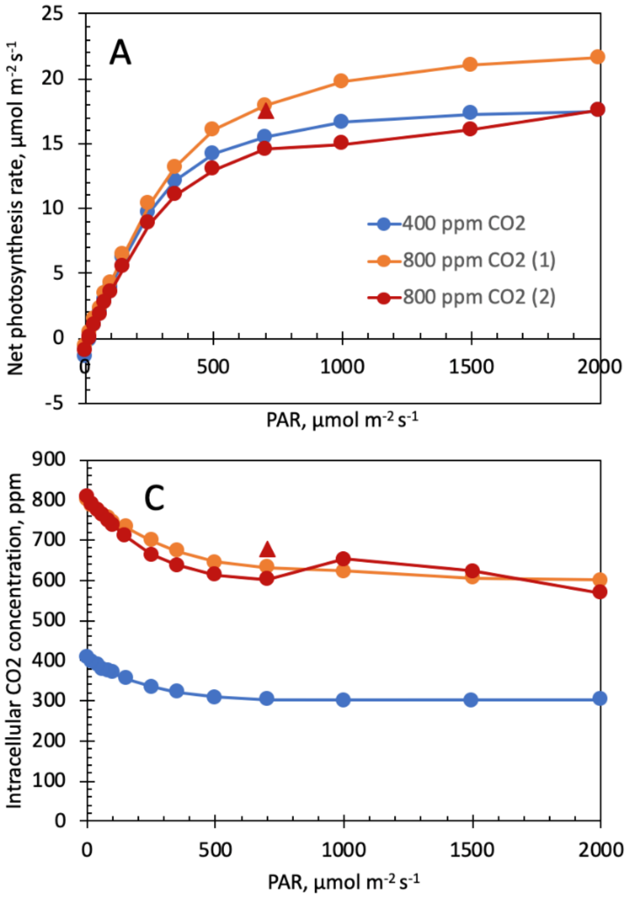


Figure 23. The light response curve of Chrysanthemum grown and measured under two CO2 concentrations of 400 (blue data points) and 800 (orange and red data points) ppm respectively.

There are plenty of literature that shows that photosynthesis is boosted by elevated CO_2 concentration. The elevated CO_2 also allows the plant to lower the stomatal conductance to conserve water. However, too low stomatal conductance can also induce stomatal limitation of photosynthesis. When comparing measurements of photosynthesis at 400 ppm CO_2 (Figure 23 A, blue data) to 800 ppm CO_2 (The light response curve of Chrysanthemum grown and measured under two CO_2 concentrations of 400 (blue data points) and 800 (orange and red data points) ppm respectively.

A, orange data) photosynthesis at boosted by almost 20% in *Chrysanthemum* at high light. The measurement at 800 ppm CO_2 shows the expected lower stomatal conductance (The light response curve of Chrysanthemum grown and measured under two CO_2 concentrations of 400 (blue data points) and 800 (orange and red data points) ppm respectively.

B) but because of the high atmospheric CO_2 the intracellular CO_2 was almost double as high as when measured at 400 ppm CO_2 (Figure 23 C). The electron transport rate is co-regulated with the CO_2 assimilation (Figure 23 D).

A second plant measured at 800 ppm CO_2 (Figure 23 A-D, red data) showed a different pattern, though. When first mounted in the cuvette the leaf had a stomatal conductance (Figure 23 B, red triangle) similar to that of the plant measured at 400 ppm CO_2 (Figure 23 B, blue data), and the rate of net photosynthesis (Figure 23 A, red triangle) was the same as the first plant measured at 800 ppm CO_2 (Figure 23 A, orange data). The stomatal conductance immediately started to decrease stabilized in the range 100-150 mmol m^{-2} s^{-1} (Figure 23 B, red circles) and photosynthesis ended up being slightly lower than the leaf grown and measured at 400 ppm CO_2 (Figure 23 A, *cf*. red and blue data).

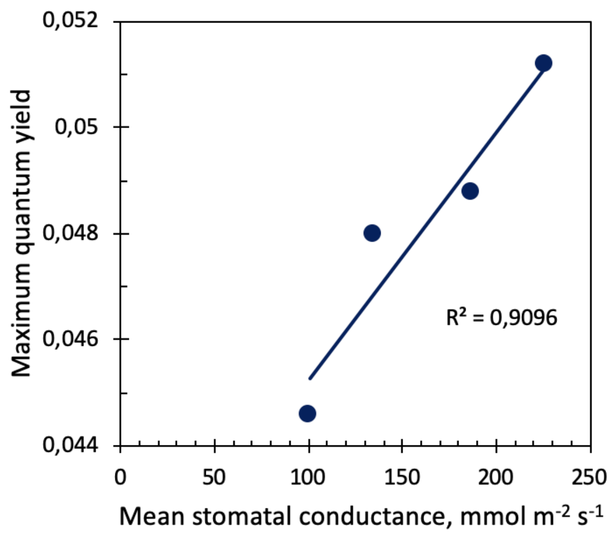


Figure 24. The relationship between the maximum quantum yield of photosynthesis and the average stomatal conductance in PAR = 20-100 µmol m-2 s-1, where the maximum quantum yield is determined.

This data set (with one more data point) also illustrates how the maximum quantum yield of photosynthesis is negatively affected by low stomatal conductance (Figure 24).

This very clearly shows how important a healthy stomatal conductance is for how well the climate conditions can be transferred into the highest possible photosynthesis at the given climate conditions. It highlights the need for continuous elaboration on how thermography can be used to optimize the growth conditions. It is possible to determine differences in stomatal conductance within pictures and when measured at the same humidity conditions. The stomatal conductance is not just the size of the stomata apertures, though. It is related to Ohm's law of electricity V = I x R, where the V is the potential difference, I is the current and R is the resistance, which again is R = 1/g, where g is the conductance. The analogy in leaves is the stomatal conductance (g_s) for g, the transpiration rate (E) for the current and the vapour pressure deficit (VPD) for the potential difference. This means that g_s = E/VPD. The parameter that determines the leaf temperature at any given air temperature is the transpiration rate, E, since it is the evaporation of water that cools the leaf tissue. Therefore, the same numeric g_s can be caused by different combinations of E and VPD, which is why thermography cannot be used as a direct measure of g_s under varying climate conditions.

In a recent publication (Iseki and Olaleye, 2020[7]) an extended calculation of a new indicator of g_s (Gsl) has been developed, where leaf and air temperature, relative humidity and solar radiation are included. Further investigations are needed to evaluate if these new calculations can be used to improve the use of thermography in varying climates.

4.6 Wireless sensors as input to the control strategy

4.6.1 Wireless sensors as the input to the control strategy

Wireless sensor technology is a valuable and interesting tool to assist the traditional climate control strategy in greenhouses. During recent years, wireless sensors have also become more available for the greenhouse growers. The reason is that some companies have specialized in developing portable robust sensors with a high range that can withstand the, sometimes harsh, conditions in the greenhouse. Wireless sensors are now found at low prices and with an intuitively easy-to-understand setup and data platform. Furthermore, the mobile 4G/5G network has become stronger allowing a more stable data transfer to the cloud. In the project we have worked with wireless sensors from the companies 30Mhz and SiGrow. The sensors measure light intensity, temperature, humidity and CO_2 concentration continuously and upload data to a central server platform.

Climate control in greenhouses is based on defining setpoints for temperature, light, CO_2 and humidity, which is then controlled automatically, by the use of the technological installations in the greenhouse, such as screens, windows, lamps, heating pipes etc. Feedback control is delivered by a single central climate station, often placed in the middle of the greenhouse. This makes the greenhouse climate control easy to work with, and data easy

[7] Iseki K and Olaleye O (2020) A new indicator of leaf stomatal conductance based on thermal imaging for filed grown cowpea. Plant Production Science 23: 136-147.

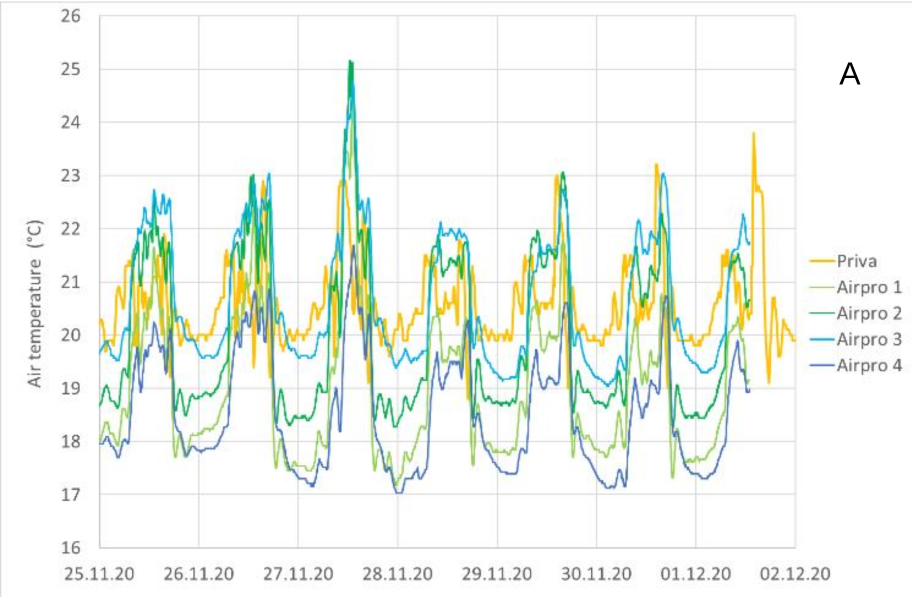
to interpret. However, the central climate data collection does not provide any information about the horizontal local variation in climate conditions close to the plant canopy. A variation which can often be quite large, due to especially the influence of windy weather from different directions, poor insulation of the greenhouse construction, or simply continuously occasions of draughts due to door or window opening.

4.6.2 Wireless sensors detect local deviations from the climate control set points

By placing the wireless sensors on specific locations in the greenhouse, the grower can collect information on whether the current climate control settings in the climate computer result in the desired greenhouse climate. If this is not the case, action can be taken to change the setpoints with the purpose of getting a more homogenous climate. Alternatively, the local conditions in specific areas of the greenhouse can be changed by installation of more or less permanent screens, lamps or other technical installations with the purpose of improving the homogeneity of the climate or saving energy. At the nursery ByGrowers, local variation was followed during a period of one month in winter (Figure 25). The greenhouse had the following setpoints: Air temperature 20°/20°C night/day, and CO_2 min. 300 ppm, max 1000 ppm with deduction for window opening and wind speed. The humidity conditions in the greenhouse was not controlled. The sensors were placed on a transect through the greenhouse, with one sensor placed close to the climate station, one sensor placed in the middle of the greenhouse, and two sensors placed closed to the east and west sidewalls. A simple comparison of the temperature data from the wireless sensors with the data from the Priva climate station, made available through InfoGrow 2.0, revealed that the temperature inside the greenhouse deviated a lot more from the setpoints than expected (26A).

Figure 25. The greenhouse at 'by growers' where the four sensors were used to detect local variations in the microclimate

The night temperature set point was 20°C, which was also obtained according to the Priva climate control station, but the wireless sensors revealed that the night temperature at local positions, and closer to the plant canopy was closer to 18°C, and at the position close to the west sidewall down to 17°C. Furthermore, the humidity, which was not controlled in the greenhouse, increased up to 100%, also in the area close to the west sidewall (26B). High humidity conditions, especially in combination with low temperature can result in condensation of water on the leaves and increasing the risk of fungal diseases. A local action to prevent this in the critical area of the specific greenhouse could be relevant. For example, it could be an good idea to insulate the west sidewall of the greenhouse.



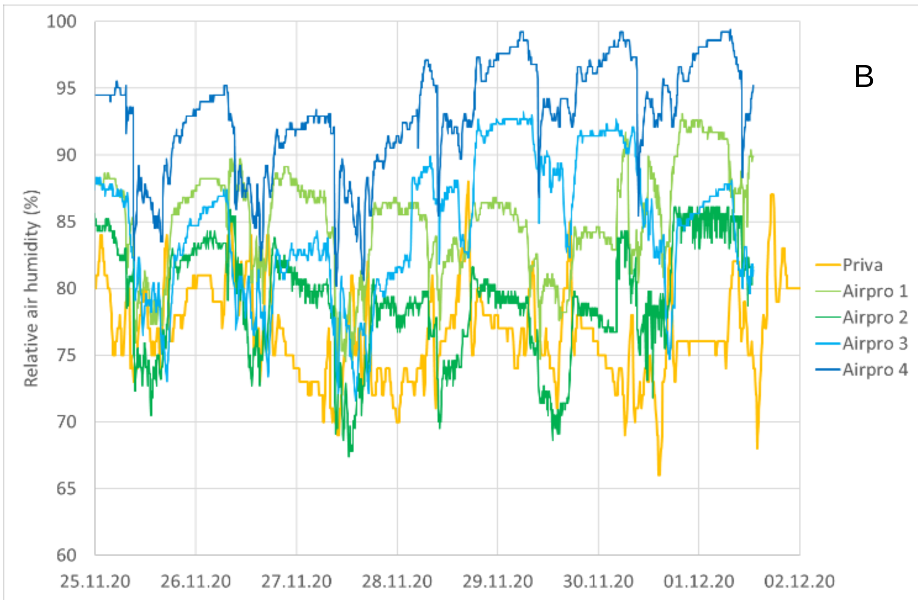


Figure 26. Air temperature (A) and humidity data (B) from climate station (Priva - yellow) and the four sensors placed on a transect through the greenhouse: Airpro 1 (east sidewall), Airpro 2 (close to Priva climate station), Airpro 3 (middle of greenhouse).

In the data from the Priva climate station, it was also seen that although there seemed to be a temperature drop in the middle of the day, this was not fully reflected in the sensor measurements for the two sensors placed close to the canopy in the middle of the greenhouse (Figure 26 and Figure 27). The temperature drop may reflect opening of screens in order to let more light in, which also result in an increased use of energy for heating. This temperature drop was less severe close to the plant canopy in the middle of the greenhouse, whereas it was more pronounced close to sidewalls, where also the air temperature were in general lower (Figure 26 and Figure 27). This demonstrates that the opening of screens to let more light in, may not have the expected effect on plant performance in all areas of the greenhouse. Higher light conditions should be followed by high temperatures to have a positive effect on transpiration and photosynthesis. If the temperature drops as a result of opening the screens, the increase in light does not necessarily have a positive impact on the plants. Instead there is a risk of reduced transpiration and reduced photosynthesis. If the humidity is at the same time high, there is even a risk of condensation on the leaves and a higher risk of diseases. In the current case, it could be relevant only to open screens in the middle of the greenhouse, if this is possible with the current settings of the climate computer.

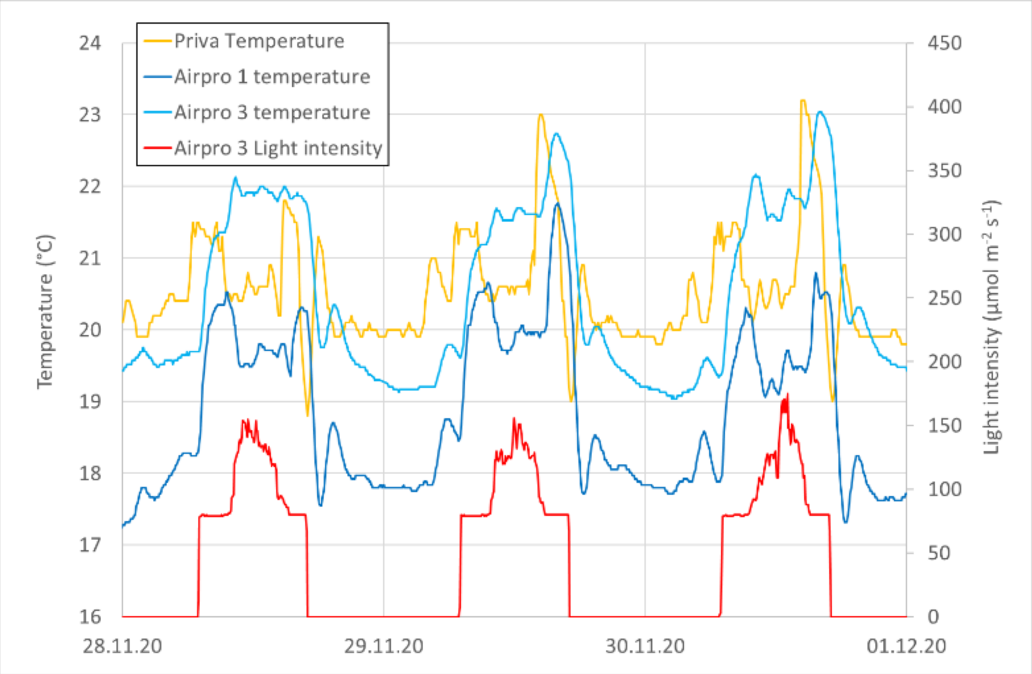


Figure 27. Temperature measured at the central Priva climate station (yellow), in the mid-dle of the greenhouse at plant height (Airpro 3 – light blue) and along the east sidewall at plant height (Airpro 1 – dark blue). The light intensity in the middle of the greenhouse is also shown (Airpro 3 - red)

4.6.3 Wireless sensors as a tool to validate climate and plant models

In the project the sensors were further used to validate the light model used in InfoGrow 2.0 (Figure 28). The current experiment was conducted at Hjortebjerg, where three different light sensors were compared to each other, and to the light intensity calculated by InfoGrow 2.0. The general experience from this experiment was that it is very important to make these validations in order to obtain qualified information of the usability of the models in InfoGrow 2.0. However, especially light intensity is very hard to measure and to estimate, as local variations across the greenhouse is extremely high and affected by many different factors such as construction, shaded areas, greenhouse coverings, distance of the sensor to the canopy and the lamps, sensor type and also the logging interval of the sensor, which determines the number of data points. In the coming years, we expect to use the wireless sensors to gain more information on how well the models in InfoGrow 2.0 reflect the current conditions in different nurseries, and the sensors will surely have a large role in obtaining this knowledge and experience.


Figure 28. The greenhouse at 'Hjortebjerg' where the sensors were used to validate the greenhouse light model

4.6.4 Wireless sensors as a tool to detect specific problems in the production

During the project period, the wireless sensors were also used to detect specific problems in the production at other nurseries. In one case, the sensors were used to study the microclimate in the production of campanula differing in flower development across the same table. Fans seemed to cause a variation in wind speed across different parts of the table. However, the effect of the fans on the microclimate was not possible to detect, due to other factors affecting the microclimate in the greenhouse. Therefore, we concluded that the very small deviations from the norm are not easy to detect in variable greenhouse conditions. In another case the sensors were used to measure light and humidity conditions under plastic coverings used to protect the rooting of cuttings. In this case it was possible to measure differences in light intensity underneath the different covering materials, and to take action on choosing the right covering material and decide how to use it properly in order to improve the quality of the small plantlets.

Our overall experience from these cases are that wireless sensors can be used in many different ways in order to gain knowledge about different challenges in the production of plants. They accomplish advice on different aspects of the production, and as a decision support tool making it easier to measure what is actually going on, in different and local areas of the greenhouse. The measurements often lead to discussions on how the climate conditions can be improved, and what actions need to be taken to improve them.

5. Utilisation of project results

The results from itGrows 2.0 will in the near future be used both in the new project Greenhouse Industry 4.0 and in two GUDP funded projects, “Bæredygtig klimastyring I væksthuse” (“Sustainable climate management in greenhouse production”) and “MicDoc”. In both projects, the developed software will be used to document the use of energy and to find possibilities for minimizing the use of energy.

The current version of InfoGrow 2.0 and Virtual Greenhouse has been presented for Senmatic’s worldwide network of distributors in an online meeting in December 2020. The feedback was extremely positive, and the distributors in the USA, UK, and Greece asked us to make a plan for how we can test the software in their countries. We will find a way to do a test as soon as possible.

After the project, the software will be licensed by the Danish Technological Institute, but in close cooperation with Senmatic and HortiAdvice. We are working on making even more close cooperation between Senmatic, HortiAdvice, and the Danish Technological Institute in marketing the developed software.

In December 2020, we agreements were made to on install our software in seven Danish nurseries in different R&D projects, and we are negotiating a commercial license with additionally three Danish nurseries. The expectation is that all three will buy a commercial license, and that we will install it at the beginning of 2021.

The world market for decision support systems aimed at the Greenhouse Industry is developing fast in these years. When we applied for the project, there were almost no competitors, but in the last two years, we have seen some new solutions on the market. The main competitors now are Pylot and Sion from the Netherlands and HortiEnergy from France. Pylot has ideas that can be seen as some of the ideas in InfoGrow (online management), while Sion and HortiEnergy are more like our Virtual Greenhouse (offline simulation). InfoGrow 2.0 and Virtual Greenhouse are the only solutions that cover both online management and offline. As our solution is the only one covering both aspects of the production, we are confident that we have excellent possibilities for selling our solution. This will be strengthened even more in our ongoing work in the project Greenhouse Industry 4.0 that will introduce several new options in our solution.

The developed software will be used as part of the greenhouse growers' energy management. We are confident that when the growers use the software, they will realize possibilities for saving energy without influencing the plant production and that, therefore, also will utilize them.

Project conclusion and perspective

itGrows 2.0 has developed two software systems aimed at energy management in greenhouse production. The systems are ready for a first commercial release in Denmark but will soon also be available in other countries. The software will be marketed in cooperation between Senmatic, HortiAdvice, and the Danish Technological Institute. The market's interest is remarkable, but continued development is needed to have a broader interest in the market. Therefore, the partners have already applied and received a EUDP-grant for a follow-up project with the title "Greenhouse Industry 4.0."

The project has met the project's objective to develop an energy management system for the greenhouse industry to help the growers in their energy and plant management.

6. Appendices

In the appendix, we have included four technical papers presenting the work for Danish technology providers and growers.

Kjær, K. H., Aaslyng, J. M., & Pedersen, J. S. (2019). Digitale løsninger til væksthusproduktion. *Gartner Tidende*, 28–29.

Kuehn, A., & Aaslyng, J. M. (2020). Nye digitale muligheder i væksthus. *Gartner Tidende*.

Bærenholdt, O. J., & Aaslyng, J. M. (2020). Det Virtuelle Væksthus. *Gartner Tidende*.

Digitale løsninger til væksthusproduktion

Programmet InfoGrow 2.0 skaber overblik over produktion og energiforbrug i hverdagen, og understøtter simuleringer af fremtidige energibesparende tiltag

Katrine Heinsvig Kjær,
Jesper Mazanti Aaslyng og
Jakob Skov Pedersen,
Teknologisk Institut,
kkja@teknologisk.dk

Regeringen har en vision om, at Danmark skal være uafhængig af fossile brændsler (kul, olie, gas) i 2050. Det betyder, at en større og større andel af energien i fremtiden vil blive baseret på vedvarende kilder som vind, sol, biomasse og geotermi.
På Gartneriet Hjortebjerg kender de allerede til problemstillingen, da gartneriet ligger langt væk fra fjernvarmeledningsnettet. Det betyder, at de allerede har investeret i grøn energi og længe har brugt en stor del af deres tid på at studere elpriser og vejrudsigter for at kunne optimere planteproduktionen i forhold til energiforbruget. Med regeringens grønne omstilling vil dette også i højere grad blive aktuelt for andre gartnerier i Danmark.

Figur 2. Et eller flere vækstometre viser aktuelle værdier, samt grænseværdier for valgte parametre som for eksempel lufttemperatur, lys, CO_2, fugtighed, fotosyntese, tid til salg eller høst, gråskimmel risiko, produktionseffektivitet eller energiforbrug.

På Teknologisk Institut har vi fokus på den digitale udvikling, samt udfordringen med klimastyring og energiforbrug i gartnerierhvervet. Vi er derfor i fuld gang med at udvikle en softwareløsning, der består af to programmer.

InfoGrow 2.0 er et program, der på basis af klimacomputerens indsamling af data, kan beregne en række parametre, som kan hjælpe gartneren med at tage beslutninger om ændringer, der kan reducere energiforbruget og optimere planteproduktionen i en verden med skiftende elpriser og klima. Simuleringsprogrammet 'Det Virtuelle Væksthus' bruger de samme data til at vurdere fremtidige effekter af energibesparende tiltag.

En digital hjørnesten

I figur 1 er vist et par klip fra programmet. Efter individuel opsætning viser programmet energiforbrug og planteproduktion for hver enkelt afdeling i gartneriet. Det er muligt at tilpasse systemet til det enkelte væksthus og bestemme, hvilke parametre som brugerfladen skal vise. Det gør systemet meget brugervenligt.
Arbejdsprocessen starter med, at gartneren indtaster data om væksthusets fysiske forhold i programmet. Herefter vælges grænseværdier for de valgte parametre. De valgte parametre kan for eksempel være produktionseffektivitet i form af 'gram plantevækst/kWh', energiforbrug til lamper og varme i 'kWh/dag' eller 'antal dage til salg eller høst'. Parametrene vises i form af speedometre, eller 'vækstometre' som vi har valgt at kalde dem (figur 2).
Vækstometrene kan vise data for de seneste 24 timer, eller for en længere periode. De kan derfor bruges aktivt af brugeren til at vise, om alt er, som det skal være, eller om der bliver brugt for meget energi på produktionen, og om det er muligt at nå forventet produktionsmål og leveringsdato. Inden for kort tid vil den nye version kunne indsamle data og viden fra forskellige typer af klimacomputere, produktionsplanlægningssystemer og web-baserede data

Figur 1. To klip fra programmet der giver en oversigt over, hvordan det går med planteproduktion og energiforbrug i hele gartneriet (bagerst) samt detaljer for en enkelt afdeling (forrest)

Deltagere i ItGrows 2.0 projektet er både gartnerier, forskningsinstitutioner og konsulentvirksomheder.

som vejrudsigter og elpriser. InfoGrow vil på den måde danne digital hjørnesten i produktionen.

Det Virtuelle Væksthus

I programmet Det Virtuelle Væksthus kan man teste effekten af energibesparende tiltag. For eksempel effekten af at ændre ventilationstemperaturen, skifte til LED lamper eller installere et nyt energigardin.
Programmet er et Excel program, der benytter komplicerede modelberegninger til at sammenligne energiforbruget imellem det eksisterende og det energibesparende setup. Programmets styrke er netop at visionære ideer kan testes virtuelt, før der investeres.

Udvikling er hårdt arbejde

Programmering og modellering er de grundlæggende elementer i udviklingen af InfoGrow 2.0. Oveni det kommer det komplekse sammenspil imellem de plantefysiologiske modeller i modelleringsprogrammet, det delvist uforudsigelige vejr, klimaet i væksthuset, klimastyringen varetaget af gartneren og klimacomputeren, og ikke mindst energiforbruget. Udviklingen af så komplekst et program kræver masser af hårdt arbejde og ikke mindst god koordinering imellem de forskellige projektpartnere for at få det til at lykkes. Programmet skal være gennemprøvet og testet, før det kan søsættes, og derfor har det også taget så lang tid at nå frem til det produkt, vi står med i dag. Vi glæder os rigtig meget til at præsentere det for gartnerierne. Første gang bliver på IPM -messen i Tyskland, men vi planlægger også et dansk seminar i løbet af 2019. ■

ItGrows 2.0

De digitale softwareprogrammer udvikles i projektet ItGrows 2.0, der er et samarbejde mellem gartnerierne byGrowers og Hjortebjerg, Aarhus og Københavns Universitet, samt NB Data, HortiAdvice og Teknologisk Institut. Projektet er støttet af EUDP programmet under Energistyrelsen.

Nye digitale muligheder i væksthus

Det tre-årige projekt IT-Grows 2.0 er ved at slutte, og resultaterne byder på nye muligheder for at få et bedre overblik over energiforbrug og tilvækst på afdelings/hus-niveau, samt hjælp til at styre produktionen

Anker Kuehn, Teknologisk Institut,
ankk@teknologisk.dk og
Jesper Mazanti Aaslyng,
jeaa@teknologisk.dk

Som en væsentlig del af projektet er der udviklet to softwareprogrammer "InfoGrow 2.0" og "Det Virtuelle Væksthus". Denne del beskriver InfoGrow 2.0. InfoGrow beregner og viser hvordan energiforbruget og tilvæksten er i den enkelte afdeling. Alt der skal til, er en start opsætning af de enkelte afdelinger, og adgang til de klimaregistreringer klimacomputeren løbende foretager. Derefter vil programmet beregne energiforbrug og fotosyntese for hver afdeling. Data der kan bruges til at sammenligne afdelingerne indbyrdes. Man kan se både de aktuelle forhold og forholdene i en selvvalgt periode. Det giver et let overblik over om alt kører, som det skal, eller om der er noget der kræver yderligere opmærksomhed.

Mange data - ringe sammenhæng

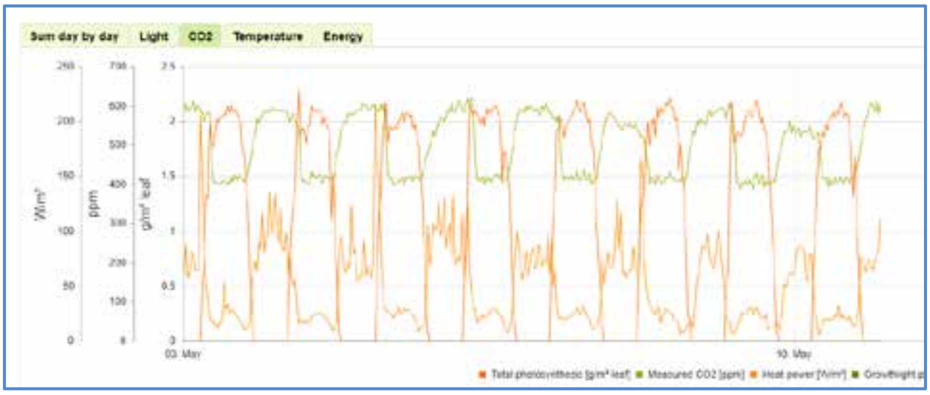
I gartnerier bruges mange forskellige programmer, som beskriver klima og energi i forhold til produktion, men med hver med sit formål; klimastyring, produktionsplanlægning, budget og analyser. Disse fungerer udmærket hver for sig, men indeholder data, der skal indtastes to gange eller data, der med fordel kunne bruges i anden sammenhæng.
Der mangler med andre ord integrering. Hvis realiserede kulturdata digitaliseres og samles med data for udførte vækstreguleringer, kan disse data udnyttes til forbedrede forudsigelser af kulturtid, der tager hensyn til det aktuelle udeklima, og udførte vækstreguleringer.
På den måde kan produktionsstyring styrkes, hvilket er meget vigtigt i ordreproducerende virksomheder. Og som sidegevinst kan der ud fra de samme data genereres udskrifter, der opfylder krav til sprøjtejournal, og data til MPS.

Den digitale log

Der er indarbejdet en mulighed for digitalt at registrere begivenheder i systemet, og det giver særdeles mange nye muligheder. Fordelen ved at registrere digitalt er, at data bliver tilgængelige for sammenstilling med klimadata, hvorudfra der kan laves statistiske analyser.
Alle begivenheder kan registreres, men

Figuren viser tre fiktive afdelinger og status på hvordan produktionen lever op til de grænser brugeren selv har sat. Jo flere røde felter der er, jo mere er der behov for yderligere opmærksomhed.

Hvis der er behov for at kigge videre på hvad der gemmer sig bag et rødt område, kan der åbnes en række tabeller og grafer, hvor data er mere detaljerede. Disse viser sammenhængen mellem for eksempel fotosyntesen og brugen af vækstlys, eller energiforbruget når gardinerne trækkes fra om morgen. Mulighederne er mange.



det er vigtigt, at man ikke registrerer mere, end der bruges videre. En begivenhed kan i denne sammenhæng være noget, der knytter sig til en hel afdeling, for eksempel plantebeskyttelse, eller det kan være noget der knytter sig til et enkelt plantehold, for eksempel vækstregulering. Det kan også være registrering af at et plantehold er flyttet til en anden afdeling, eller at planteholdet registreres salgsklart. Definitionen af planteudvikling sker i det enkelte gartneri, så det

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kan være både udvikling, som "tre åbne blomster" eller plantestørrelse, som "minimum to ranker på 15 cm".
Begivenheder kan altså tilpasses den enkelte virksomheds behov, så der kun registreres det der behov for.

Det kan Log-systemet bruges til

Basis information er, at InfoGrow kan vise energiforbrug og klimaparametre, herunder også bearbejdede data for eksempel fotosyntese. Men sammen med Log-systemet kan kulturtids-prognoser forbedres, og herunder tilbagekobling til forbedret planlægning. Det kræver en statistisk analyse, men fordi logningen er foretaget digitalt, er de nødvendige data til rådighed og kan eksporteres til videre bearbejdning.

Produktionsstyring

Allerede nu kan registrerede kulturtider holdes op mod produktionsplanen, som i øvrigt kan hentes fra GreenPlan, og takket være integreringen med de aktuelle klimaregistreringer fra klimcomputeren, kan det forudsiges hvornår et givent hold planter bliver slagsklar. I takt med flere års klima og produktionsdata registreres, vil beregningerne blive sikrere.

Målrettede rapporter

Når data for plantebeskyttelse mv indtastes i systemet, kan der oprettes rapporter, der opfylder krav til sprøjtejournaler, og rapporter der kan indgå i MPS-indberetninger, så dobbeltindtastninger undgås.
Log-systemet er så fleksibelt at hvis myndighederne på et tidspunkt forlanger en vandforbrugsdokumentation, kan loggen sættes op til at håndtere dette.

Flere funktioner på vej

Udviklingen af disse systemer foregår sideløbende via andre projekter, pt i Greenhouse 4.0. Det er her planen at integrere vejrudsigter og aktuelle energipriser fra for eksempel Nordpol i systemet. Vejrudsigterne vil forbedre kulturtidsprognoser, som dermed øger præcisionen. Og denne information kan også bruges til at reducere omkostninger til vækstlys.
Allerede nu kan eksterne sensorer kobles op via klimacomputeren, men på sigt skal det også være muligt at koble eksterne sensorer på uafhængigt, for eksempel temperatur, indendørs lysmåling, vandmålinger. ■

Det virtuelle væksthus

'Det virtuelle væksthus' er et softwareprogram, der er udviklet i projektet IT-Grows 2.0. Takket være programmet kan man simulere fremtidigt væksthusklima og dermed få en ide om konsekvenserne af investeringer

Ole Bærenholdt Jensen, HortiAdvice og
Jesper Mazanti Aaslyng,
Teknologisk Institut,
jeaa@teknologisk.dk

Det virtuelle væksthus er et program, som beregner energiforbrug og klima for gartneriets huse ud fra de sætpunkter, man har angivet – for eksempel temperatur, RH-styring, og CO_2 styring - og de tekniske informationer, man har angivet for væksthuset

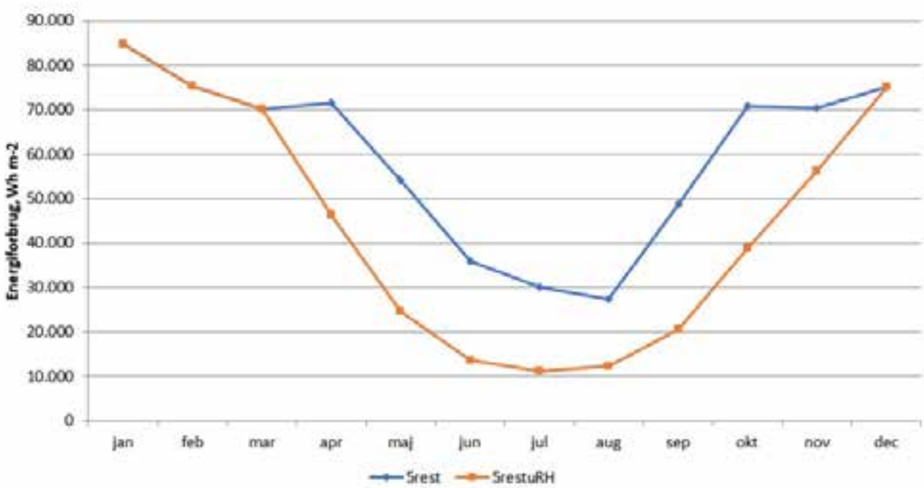
Leg med mulighederne
Når man på denne måde har beskrevet væksthuset "virtuelt" i computeren, kan man begynde at "lege" med mulighederne for fremtiden – det man kalder simulering. Her er nogle eksempler:
Hvis man gerne vil ændre i gardinstyringen, kan man virtuelt opsætte nye gardiner, og ikke blot beregne energibesparelsen i forhold til det gamle gardinanlæg, men også de nye lysforhold, ændret temperatur i perioder af året, og den tilhørende beregnede fotosyntese. Det vil sige konsekvenserne af de nye klimaforhold for planterne – ud over bare at beregne energibesparelsen.

Hvis man ønsker at bygge et nyt væksthus og overvejer at opsætte kanalplader i stedet for glas på nogle eller alle husets flader, kan det have en radikal indflydelse på energiforbruget, men også på fugtighedsforholdene året rundt.
Hvis fugtigheden bliver for høj – eller perioderne med høj fugtighed bliver for lange, kan man måske overkomme problemet med øget fugtstyring, og den flotte energibesparelse man i første omgang beregnede, reduceres måske til det halve. Det kan alt sammen simuleres i programmet – vel at mærke ud fra de klimaforhold og indstillinger man ønsker for den / de kulturer der skal dyrkes i væksthuset.

Muligheder for simulering
Det er muligt at udføre simuleringerne på:

- Klimadata opsamlet af den eksisterende klimacomputer (kan bruges til kontrol af om beregningsprogrammet er indstillet rigtigt, idet man kan sammenligne det med det aktuelle klima og det energiforbrug, man målte i samme periode)
- Standard klimadata fra et standard-år nær gartneriet (såkaldte DRY-data)
- Klimadata fra udlandet, for de gartnerier, der har brug for beregninger på deres udenlandske afdelinger eller for teknologileverandører der sælger til udlandet.

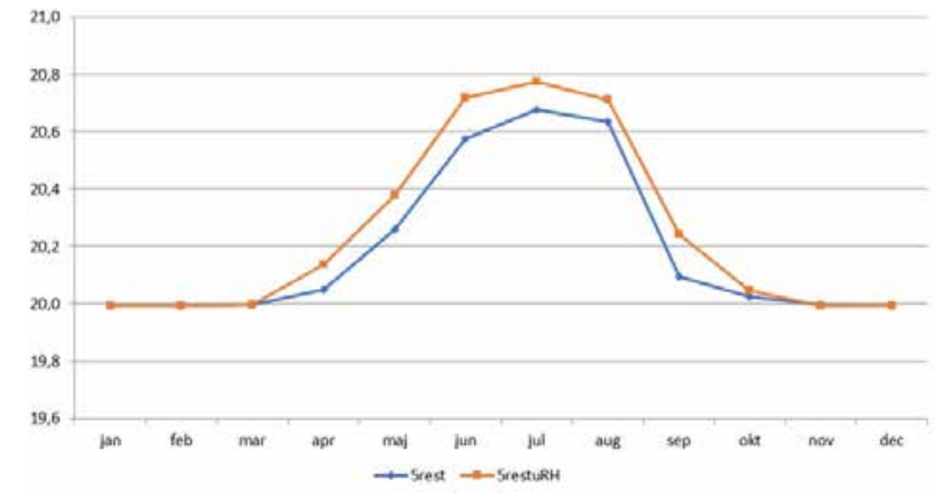
Projektet er ikke slut endnu, og der foregår stadig test af det virtuelle væksthus, men allerede nu kan potentialet ses.



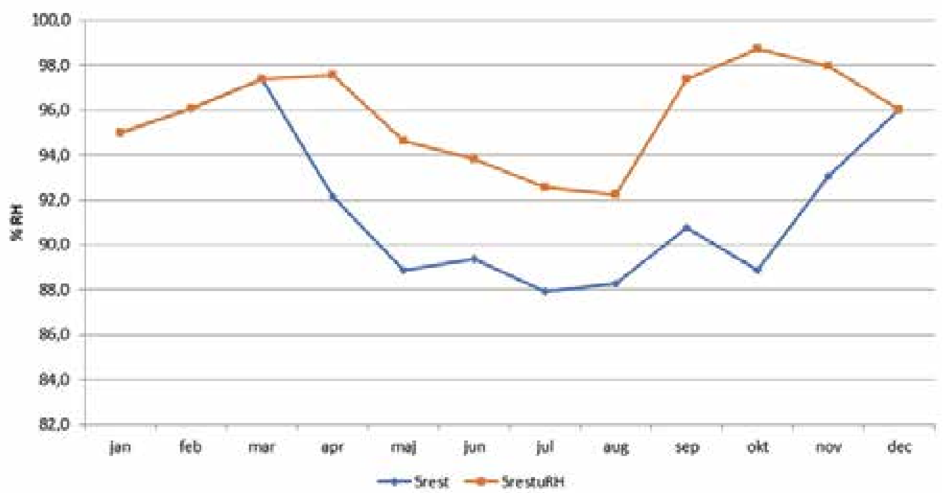
Figur 1 Månedligt energiforbrug til opvarmning beregnet for klimaindstilling uden fugtstyring (gul) og med fugtstyring (blå).

Hvordan afviger beregningsmetoden så fra den kendte "P-værdi-baserede" model?
P-værdi modellen anvendes i stor udstrækning til beregning af energibesparelse ved for eksempel tilskudsansøgninger. Det er en beregningsmetode, som er vel gennemprøvet – og den bygger på u-værdier på de anvendte materialer og det påtænkte temperatursætpunkt, i forhold til udetemperaturen, som beregningsmotoren i det virtuelle væksthus. Men P-værdi modellen er en statisk model, hvorimod det virtuelle væksthus også tager højde for, at der er planter i væksthuset, og at disse påvirker, og bliver påvirket af klimaet.
Der, hvor det det virtuelle væksthus har sin styrke, er at det klima, der kan forventes time for time i væksthuset også bliver beregnet, således at det forventede resultat for klimaet, som planten udsættes for ved de nye indstillinger (eller investeringer), også kan beregnes sideløbende med en nøjagtig energiforbrugsberegning, og tages med i beslutningsprocessen.
Se de månedsopdelte eksempler herunder (Figur 1,2 og 3 blå kurve er med fugtstyring)

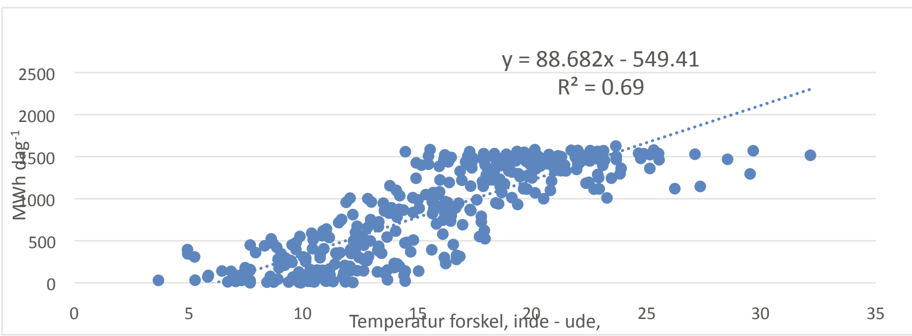
Analyser produktionen
Det virtuelle Væksthus kan også bruges til at analysere klimaet, der har været i væksthuset i det seneste år, eksporteret fra Senmatic eller Priva klimacomputeren. I det virtuelle væksthus kan data delvist automatiseret analyseres med det formål finde særlig udfordringer i klimastyringen. Det kan være fugtighedsforhold, der skaber mulighed for vækst af sygdomme, perioder med særligt store energiforbrug eller data for, hvordan produktionen kan times ved hjælp af temperatursummer eller lyssummer.
Det er ret fleksibelt og kan tilpasses de aktuelle behov. Figur 4 viser et års energiforbrug delt på årets dage. Programmet fortæller ud fra figuren, hvilke dage der er brugt mest energi i forholde til forskellen i ude- og inde-temperatur. Når man kender det, kan man vurdere, om man kan gøre noget ved det. Det kan for eksempel være fugtstyringen eller særligt dage med høj vindhastighed der skal arbejdes videre med. ■



Figur 2 Gennemsnitlig månedlig beregnet indetemperatur (°C) for klimaindstilling uden fugtstyring (gul) og med fugtstyring (blå).



Figur 3 Gennemsnitlig månedlig beregnet Relativ fugtighed (RH) for klimaindstilling uden fugtstyring (gul) og med fugtstyring (blå).



Figur 4 Analyse af energiforbrug i forhold til temperaturforskel mellem inde- og udetemperatur.

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