Dynalight Next Generation

Smart Grid Ready Energy Efficient Lighting System for Green House Horticulture

Final project report

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1. Project details

Project title	Smart Grid Ready Energy Efficient Lighting System for Green House Horticulture (Smart Grid Ready Energiomkostningffektiv Kunstlysstyring til Væksthusgartnerier)
Project identification (program abbrev. and file)	64012-0148
Name of the programme which has funded the project	EUDP and GUDP (shared funding)
Project managing company/institution (name and address)	The Maersk Mc-Kinney Moller Institute University of Southern Denmark Campusvej 55 5230 Odense M Denmark
Project partners	**Research partners:** Professor, WRT., Ph.D. Bo Nørregaard Jørgensen and assistant professor Ph.D. Jan C. Sørensen, Center for Energy Informatics, The Maersk McKinney Moller Institute, University of Southern Denmark Professor, WRT., Ph.D. Carl Otto Ottosen and postdoc Katrine H. Kjær, Institute of Food Science, Aarhus University Associate professor, Ph.D. Eva Rosenqvist, Department of Ecology and Agriculture, University of Copenhagen Senior researcher Carsten Dam-Hansen, Department of Photonics Engineering, DTU **Industrial partners:** Dong Energy Lindpro A/S Philips Green Tech Solutions ApS – Resigned from the project ConWx ApS Gartneriet Knud Jepsen A/S Gartneriet Rosa Danica A/S Gartneriet SOGO Team ApS – bankruptcy autumn 2015 Legro Gartnerierne A/S
CVR (central business register)	29283958
Date for submission	

2.   Short description of project objective and results

2.1   English version

The project aims to develop the next generation of energy cost-efficient artificial lighting control that enables greenhouse growers to adapt their use of artificial lighting dynamically to fluctuations in the price of electricity. This is a necessity as fluctuations in the price of electricity can be so large that it directly affects the production costs. The project results show that the newly developed lighting control software, DynaLight NG, allows greenhouse growers to adapt their use of artificial lighting to market variations in electricity prices without negative impacts on plant quality or production time. The electricity savings that DynaLight NG can achieve depends on the installed lamp type. When used together with conventional SON-T lamps DynaLight NG can achieve an electricity savings of 25% compared to traditional artificial lighting control. The project results also show that shifting from SON-T to LED lamps can result in a further reduction of 50% reduction in electricity consumption.

2.2   Danish version

Det er projektets formål at udvikle næste generation af energiomkostningseffektiv kunstlysstyring, der gør væksthusgartnerierne i stand til dynamisk at tilpasse deres brug af kunstlys til udsvingene i elprisen. Dette er en nødvendighed, da udsving i elprisen kan være så store, at det direkte påvirker produktions-omkostningerne. Projektets resultater viser at væksthusgartnerierne med den nyudviklede kuntlysstyring, DynaLight NG, kan tilpasse deres brug af kunstlys til elprisen uden negative konsekvenser for plantekvalitet eller produktionstid. Elbesparelsen der kan opnås ved brug af DynaLight NG afhænger af den anvendte lampetype. Hvis anvendt sammen med konventionelle SON-T lamper, kan DynaLight NG opnå en elbesparelse på 25% i forhold til en traditionel kunstlysstyring. Projektets resultater viser også, at et skift fra SON-T til LED lamper vil resultere i en yderlig reduktion i elforbruget på 50%.

3.   Executive summary

The project has delivered the next generation of intelligent, energy cost-efficient light control to the commercial greenhouse grower sector - DynaLight NG (Next Generation), which by combining 3-day weather forecasts, Smart Grid-price signals and specific knowledge of selected plant species responses to dynamic artificial lighting, allows commercial greenhouse growers to provide system services to the grid without compromising production time and plant quality. The project showed that the frequency by which commercial greenhouses can provide system services depends on two factors; the cultivated plant species, as well as the applied lamp type. Plant species have different reaction times to initiate their photosynthetic systems, so commercial greenhouse growers, cultivating plants with a short reaction time, will be able to provide ancillary services with a higher frequency. Similarly, a transition to modern LED lamps will allow commercial greenhouse growers to provide ancillary services in the form of up- or downregulation far more often than with conventional SON-T lamps, since the life of the SON-T lamps depends on how often they are turned on and off within the same operating hours. The delivery of such ancillary services are examined as part of DONG Energy's Power Hub concept and integrated via the OpenADR standard for Demand Response services.

The project has carried out experiments with dynamic light control for different configurations of SON-T and LED lights with the aim to investigate the effect of dynamic light control on plant quality and production time of different plant species. AU conducted a series of experiments using plant material from the participating commercial greenhouse growers, in order to be able to compare the effect of dynamic light control with the traditional light control used by commercial greenhouse growers.

The plants from the dynamic light control experiments at AU were fully satisfactory in terms of plant growth and development, compared with traditionally produced plants from the commercial greenhouse growers. Dynamic light control gave more compact plants and better leaf colors, especially in combination with LED lights. A transition to LED lights is therefore not expected to cause any negative effect on plant quality or production time.

DTU Photonics has characterized all lamp types used in the project, with regard to their spectral distribution, energy efficiency, and light distribution. The results show which lamp types that presently are the most cost-effective to deploy in the commercial greenhouse sector. Furthermore, the results can be used in the design and optimization of greenhouse lighting installations. The results show that LED lamps are the most effective with a reduction in energy consumption of approximately 60% compared to the old SON-T lamps. Compared with newer electronic lamps, LED lamps achieve a reduction of approximately 32-40%. Over the 3 year project period, the efficiency of LED lamps has generally been increasing by 25%. The desired dynamic control of light is significantly limited by using SON-T lamps, as they need about 15-20 minutes to warm up before they reach full brightness, and require a similar cooling period after they have been switched off, before they can be switched on again. Thus, the results show that it is necessary to limit the dynamic control to 3-hours blocks when using SON-T lamps. A much better dynamic light control can be achieved with the new LED lamps, where maximum brightness is momentarily achieved after being switched on, and which can be switched off and on very quickly.

In the last phase of the project DynaLight NG was extended to manage all climate parameters dynamically, i.e., simultaneous dynamic control of temperature, CO_2, artificial lighting, and curtains. In the previous version of DynaLight NG it was only the artificial lighting that was controlled dynamically. The new version of DynaLight NG has been used in experiments for a greater variety of plant species, including Kalanchoe, roses, chili, basil, Phalaenopsis, and Passiflora, to assess whether a fully dynamic climate control is possible for a wide selection of ornamental and edible plants without compromising the quality and production time. DynaLight NG was extended to manage all of the climate parameters, as experiments with the previous version of DynaLight NG showed that there was a need for adding more heat when using dynamic light control, than when using conventional light control. The larger heat consumption was however expected since optimal control of artificial lighting results in less light hours and thereby less heat emission from the lamps to the greenhouse. This situation is further aggravated when shifting from conventional SON-T to LED. So the electricity saving is a trade off with the increased heating expense. The new version of DynaLight NG is now extended to handle both lighting and heating control properly for the selected plant species. For use with the extended version of DynaLight NG, the project business partner ConWX has improved the accuracy of the solar irradiation prediction in their weather forecast model, so that it now takes into account seasonal fluctuations. High accuracy for the prediction of solar irradiation is required for correct dynamic light control.

The project has shown that LED light is fully suitable for growing plants. By using 100% LED lighting a part of the lost heat emission from the SON-T lamps has to be supplemented from the heating system. However, with an airborne heating system, as present at KU's test facilities, there is no need for heat compensation, but airborne heating systems is not yet common in the commercial greenhouse sector. Hence, a combination of LED and SON-T lamps can be beneficial in a transitional phase of greenhouse technologies. Furthermore, the remaining life span of an existing lighting installation has to be considered when planning a transition to LED or a combination of LED and electronic SON-T lamps, in order to assess return on investment (ROI). In the time of the project, the prices on LED were still relatively high, leading to a long ROI, but the market is changing quickly, and full LED installations may become economically feasible earlier than expected.

Based on the project's current results the project business partner Lindpro has advised and guided up to 30 growers in energy-saving lighting installations.

4.   Project objectives

The main project objective is to develop the next generation of intelligent, energy cost-efficient lighting control for commercial greenhouse growers using an innovative combination of 3-day weather forecasts, smart-grid price signals, and knowledge about plant species' specific response to dynamic control of different types of artificial lighting. The project will investigate selected plant species response to the following types of lamps: 1) traditional SON-T, 2) electronic lamps, and 3) LEDs. Effective dynamic lighting control will allow commercial greenhouse growers to adjust their use of artificial lighting to fluctuations in the inter- and intra-day electricity market prices without negative impacts on plant quality or production time. Furthermore, it will allow the commercial greenhouse growers to deliver ancillary services to the electricity grid, in particular balancing services for up and down regulation to encounter under- and over-production from fluctuating renewable energy sources, like wind and solar. The investigation of smart-grid integration and optimization of greenhouses with the electricity grid will use the Power Hub concept from DONG Energy.

This project expands the current body of knowledge on dynamic lighting control, by moving from one-day weather forecasts, single day-ahead electricity prices, a general plant response model, and conventional SON-T lamps to 3-day weather forecasts, 3-day ahead electricity price forecasts, plant species specific response models, and electronic- and LED lamps. In addition, this next generation of dynamic lighting control will be prepared for integration with the smart-grid, thereby making the greenhouses smart-grid ready.

The project divides the main objective into following four sub objectives:

- To characterize selected plant species' physiological and growth-related responses to dynamic use of different types of artificial lighting.
- To characterize the spectra and efficiency for various lighting fixtures.
- To develop the next generation of software for energy cost-efficient dynamic lighting control that facilitates smart-grid integration of greenhouses' use of artificial lighting.
- To test and demonstrate dynamic lighting control in combination with different types of artificial lighting for selected plant species in collaboration with the participating greenhouse growers.

The implementation of the projects' sub objectives were organization into following work packages:

WP1 (Funded by GUDP: Participants AU, KU, KJ, RD, Legro, Phillips, SOGO) investigates how selected plant species, including Kalanchoe, roses, chili, basil, Phalaenopsis and Passiflora, respond to dynamic use of SON-T and LED lighting. Knowledge about specific plants respond to dynamic lighting control is necessary for using commercial greenhouses to deliver demand response services to the electricity grid.

WP2 (Funded by EUDP: Participants DTU) performs characterization of various lighting fixtures energy efficiency and spectral distribution

WP3 (Funded by GUDP: Participants SDU, AU, ConWx) targets the development of the next generation of software for intelligent control of artificial lighting. The WP uses the results from WP2 in the development of new climate control strategies.

WP4 (Funded by EUDP: Participants SDU, AU, KU, DTU, Green Tech Solutions, Phillips, Lindpro, RD, KJ) addresses integration of DynaLight NG with the greenhouse climate computer from Priva and the Power Hub concept from DONG Energy, and installation and test of combinations of LED and SON-T at the commercial greenhouse growers.

To ensure optimal flow of information between work packages it was decided to have one project group instead of a separate steering committee and project groups for each work package. This decision showed to facilitate open discussion among project partners and brought the researchers close to the practical challenges experienced by the commercial greenhouse growers.

Overall, the project evolved according to plan. During the project period, the project only experienced three issues that could influence the project progress, and results. However, none of these turned out to have any major impact on the project results. Firstly, the SME partner Green Tech Solutions decided to leave the project, as they had to prioritize their resources differently. To ensure project progress SDU took over the tasks of Green Tech Solutions. Secondly, the partner SOGO Team went bankrupt. However, this happened after they had delivered their contribution to the project. Finally, Philips Lightings delivery of top-based LED lamps has been delayed beyond the last of the project's growth periods, and the planed experiments with this type of light-fixture therefore had to be abandoned. However, this was a risk that was already know at the being of the project and the project partners AU and DTU compensated by including other LED based lighting fixtures in the project.

5. Project results and dissemination of results

This section presents the project's main results along the following five activities:

- DynaLight NG next generation of energy cost-efficient dynamic lighting control.
- Smart Grid integration of greenhouse nurseries.
- Characterization of LED fixtures and efficiency.
- Characterization of plant species' responses to dynamic control of artificial lighting.
- Test and demonstration of different configuration of lighting fixtures and dynamic lighting control.

The dissemination of the project results in scientific publications and trade journals is listed in the annex.

The following sections describe the project results in more detail.

5.1 DynaLight NG next generation of energy cost-efficient dynamic lighting control

In seasonal periods when daylight in Denmark is limited and not corresponding to the amount of daylight required for optimal plant growth, commercial greenhouse growers have to use supplementary artificial lighting to ensure the necessary development of their plants. The use of supplementary artificial lighting is the commercial greenhouse growers' primary source of electricity consumption. Therefore, particularly this part of the electricity consumption is interesting to investigate in connection with minimizing costs for plant growth. Especially because plants do not need supplementary light all day, and thus there is flexibility in when artificial lighting is used. It is this flexibility that can be used to make commercial greenhouses Smart Grid Ready. However, the existing greenhouse climate computers do not support the artificial lighting to be dynamically controlled, and therefore there is a need to develop the next generation of climate control software that can advance the production of greenhouse cultivated plants beyond the present state of the art.

DynaLight NG is a next generation climate control software that optimizes the greenhouse climate based on weather forecasts, electricity prices, plant physiological models, and production goals. The optimization goal of the software is to find a trade-off between energy cost-efficient greenhouse operation and optimal use of supplemental artificial lighting to increase plant growth.

The software optimizes the use of supplemental artificial lighting over a period of three days. The electricity prices used by the simulation are composed by the actual hourly Nord Pool spot prices for the forthcoming day, and a prognosis for hourly prices for the following two days (provided by Energi Danmark). DynaLight NG provides optimized control strategies for heating, CO2, window screens, ventilation, and artificial lighting. The advanced control strategies are based on software plug-in components and can thereby be configured for specific production settings and plant species. The software is configured through its graphical user interface that offers functionality for setting up control strategies for individual greenhouse departments and graphs for viewing the actual greenhouse climate. The output of the control

strategies is optimized using advanced artificial intelligence algorithms to guarantee an optimal trade-off between the multiple control objectives.

The software works as an add-on to existing climate computers based on a well-defined Hardware Abstraction Layer (HAL). The HAL makes is easy to integrate with existing climate controllers to support the future of advanced supervisory control and data acquisition systems. The HAL provides a general application programmer interface to map sensor inputs and actuator outputs to specific third party climate controllers. Currently, DynaLight NG integrates with state of the art climate computers from the Danish company Senmatic and the Dutch company PRIVA.

5.1.1   DynaLight NG control concept

DynaLight NG is designed to control climate-related growth factors by sensing and manipulating the greenhouse climate through the use of sensors and actuators. The physical DynaLight NG setting is modelled as a combination of a control machine, a number of connection domains and a controlled domain (Figure 1).
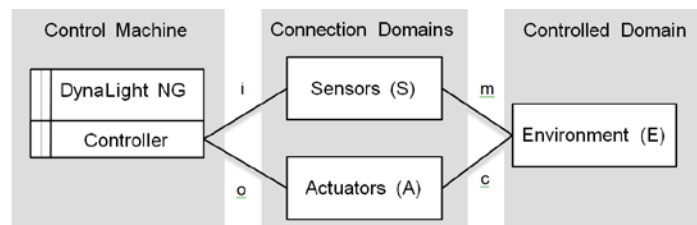
Figure 1. DynaLight NG system overview.

The control machine consists of the DynaLight NG software running on a PC that is connected to a set of climate controllers. The climate controllers are connected to sensors and actuators (Connection Domains) that interact with the indoor climate of the greenhouse (Controlled Domains). A connection domain can act as a sensor or an actuator. Sensors provide measured input information m in form of input variables i to the control machine domain. Contrary, actuators influence the physical phenomenon c in the controlled domain according to output variables o provided by the control machine. The purpose of DynaLight NG is to impose a control on the physical environment, such that certain conditions are satisfied.

The objective of DynaLight NG is determined by the system's control specifications, which typically incorporates models of the physical environment. For example, a model of the photosynthesis process of a given plant species in a greenhouse. Control specifications are formulated over a set of input variables i and output variables o connecting the control machine with the connection domains. The control specifications are evaluated continuously by the control machine in cycles as part of a control process. Each cycle is triggered at specific intervals. For each control cycle, the system perceives the environment through its sensors variable i, evaluates the control specifications, and changes the environment through its actuators to obtain the desired objective of the system. The result of a control cycle is a set of output variables o, i.e., setpoints that are written to the actuators. The actuators can change the resources in the environments based on the output variables of the control system.

5.1.2   DynaLight NG software features

DynaLight NG is a features-oriented software system divided into a number of features. Each feature encompasses an individual unit of software functionality and is implemented as loosely coupled plug-in modules. The system is categorized into five types of plug-in models: Graphical User Interface (GUI), Control Strategy, Driver, Service, and Core plug-ins.

The GUI plug-in model provides the implementation of the graphical interface that the user interacts with and is described in Section 5.1.3. The Control Strategy plug-in model provides a number of control objectives (cost functions) that have to be optimized in order to gain a coordinated output of the combined

control strategies. The Control Strategy plug-in model depends on the HAL provided by different driver implementations. Section 5.1.5 describes each implementation of the supported drivers provided out of the box in DynaLight NG. The driver implementations enable DynaLight NG to communicate with different types of climate controllers. All drivers adhere to the HAL API and can be replaced with other implementations of climate controllers or climate simulators. Data services are provided as a separate type of plug-in and integrate third-party services like weather and electricity forecast services. The basic services provided in DynaLight NG are described in section 5.1.6. Core plug-in models handle resources, data, optimization and scheduling of control cycles and the user only interact with this part of DynaLight NG through system settings.
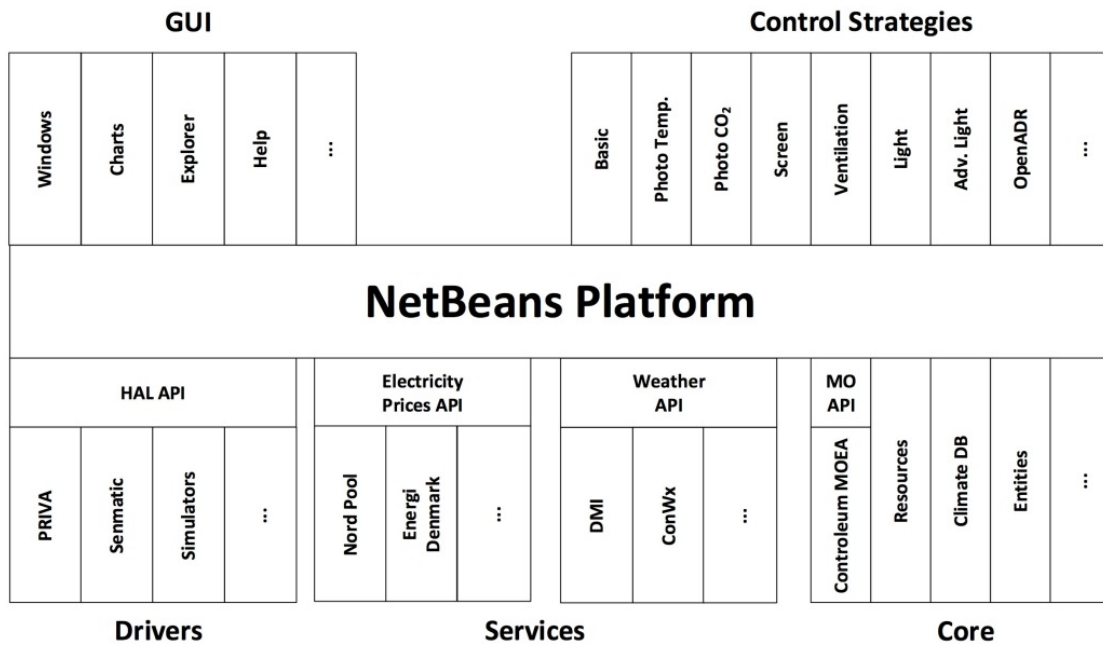
Figure 2. Features-oriented view of DynaLight NG.

5.1.3   Graphical User Interface

The main GUI is provided partly by the NetBeans Rich Client Platform and provides a generic windows docking system. By default, all windows are displayed in the NetBeans main application window. Moreover, undocking windows by using the context menu or dragging the window from the application window is possible (Dock/Undock). Docking and undocking allows for flexible window positioning. The so-called Floating Windows feature is especially useful when you are using multiple monitors. Figure 3 is a screenshot of the DynaLight NG graphical user interface (GUI). The GUI consists of a main window that is comprised of a toolbar (1), navigation tree (2), tab-based main windows (3), and a status bar (4).
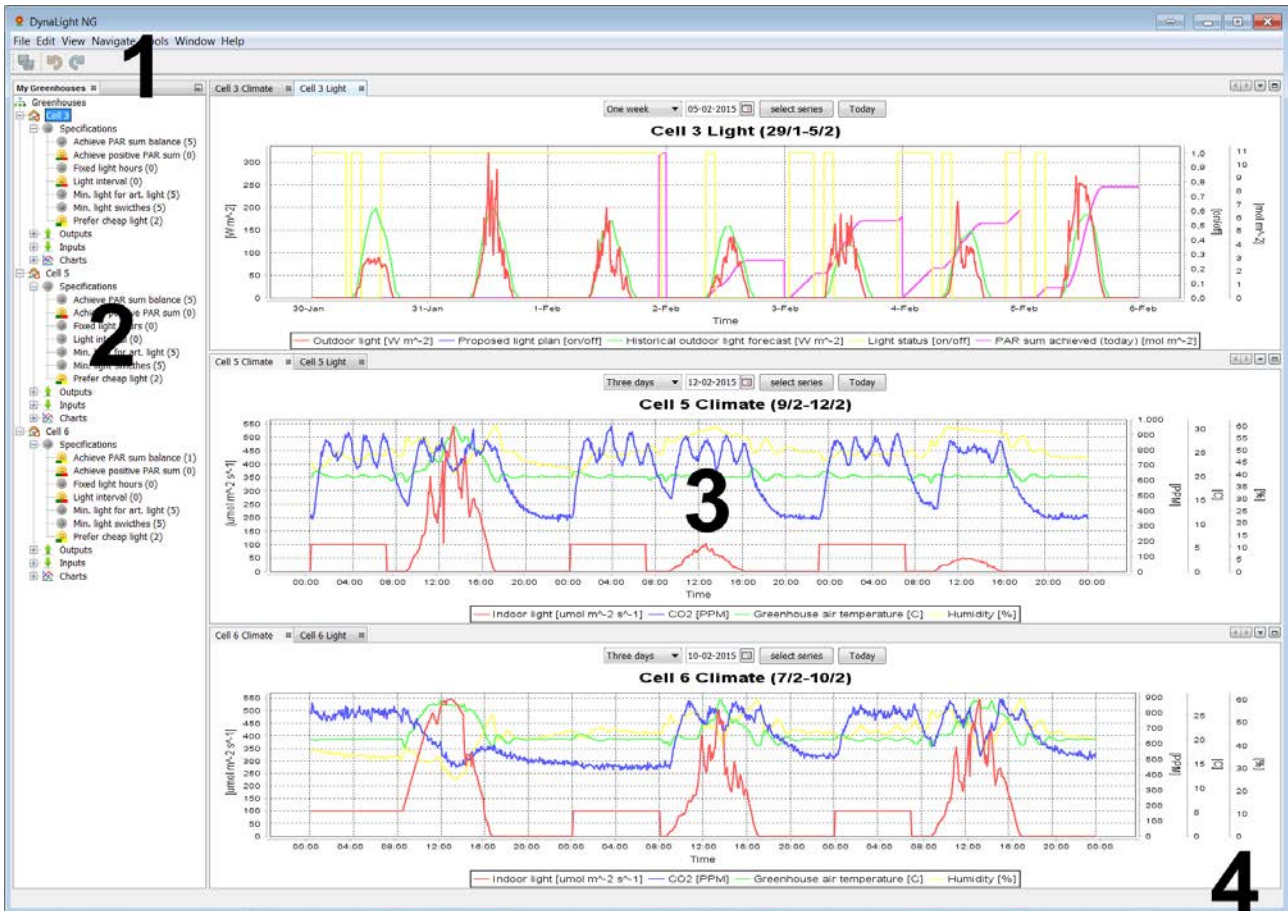
Figure 3. DynaLight NG Graphical User Interface (GUI).

The navigation three (2) provides an overview of the controlled greenhouses, see Figure 3. Each greenhouse has its own top node in the navigation tree and that is composed of the sub-nodes: control specifications, inputs, outputs, and charts, see Figure 4.
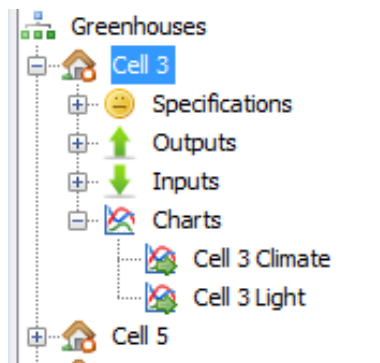
Figure 4. Navigation tree.

Subsections 5.1.3.1 - 5.1.3.6 describe how to use the Navigation tree to handle Greenhouses, Inputs, Specifications, Outputs, and display the current state of the system. Subsections 5.1.3.7 - 5.1.3.9 explain how to use tabbed based windows to illustrate data about the climate control. Finally, Subsection 5.1.3.10 describes how to interpret the system status bar.

5.1.3.1   Create greenhouse

A greenhouse is created by right-clicking the root node *Greenhouses* and clicking the *Create greenhouse* action in the pop-up context menu, see Figure 5.
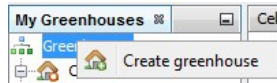
Figure 5. Create Greenhouse action.

Figure 4 shows greenhouse Cell 3 and Cell 5 where Cell 5 is collapsed. The greenhouse Cell 3 node is expanded and shows its sub-nodes: specification, inputs, outputs and charts. Besides functioning as a visual overview of specifications, inputs, and outputs, the navigation tree is also used for configuration. When a node is right-clicked, a menu of actions related to the specific node is displayed. Each of the sub-nodes can be configured separately by right-clicking the corresponding sub-node.

5.1.3.2   Manage greenhouse
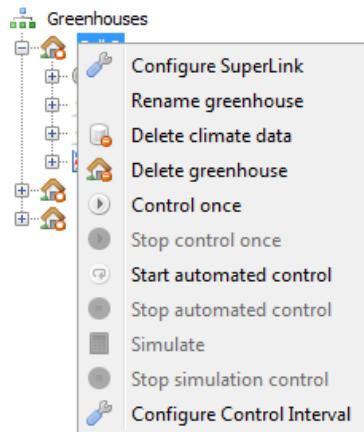
Figure 6. Greenhouse actions.

Figure 6 display the action menu for the selected greenhouse node. Actions for a greenhouse node include:
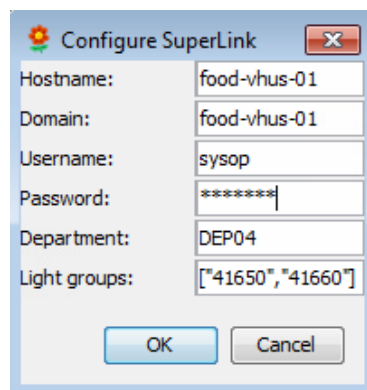
Figure 7. Configure Senmatic controller.

- *Configure* (Climate Controller Name) action is dependent on the installed climate controller plug-in. For example, Figure 7 shows the specific climate controller configuration dialog for Senmatic climate controllers. Section 5.1.5 provides more detail about each climate controller integration plug-in.
- *Rename Greenhouse* action renames the greenhouse node.
- *Delete Climate* action deletes climate data for the greenhouse.
- *Delete Greenhouse* action deletes a greenhouse and its related data.
- *Control Once* action executes one control loop of the given greenhouse configuration.
- *Start/Stop Automated Control* action starts and stops automated execution of control loops in given time intervals.
- *Simulate* action start simulation of the greenhouse configuration.

- *Stop Simulate* action stops simulation of the greenhouse configuration.
- *Export Data* action exports climate data to a comma value separated file.
- *Configure Control Interval* action configures the control loop interval in minutes. The same interval specifies how often data is updated and stored in the local climate database.

5.1.3.3 Manage inputs

DynaLight NG supports three categories of inputs: User inputs, Service inputs, and Sensor inputs (from drivers).
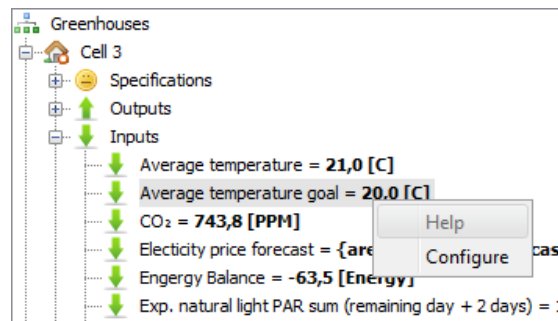
Figure 8. Configuration of a selected input.

For each user input node in the navigation tree, it is possible to right-click and select a *Configure* action. The *Configure* actions are specific for each type of input. Figure 8 illustrates right clicking on the *Average Temp. Goal* (*AvgTempGoal*) input. When selecting the *Configure* action a popup dialog box is displayed which allows the user to enter a value for the given input.

User inputs include goals and limits used in the control specifications – i.e., *Average Temp. Goal* (*AvgTempGoal*), *Photosynthesis Optimization Goal* (*PhotoOpt*), and *Maximum Temp. Limit* (*TempMax*).

Service inputs are responsible for integrating data from external services like weather forecast services, electricity price forecasts, and the open standard for Automated Demand Response (OpenADR) for smart-grid integration.

Sensor inputs represent measured values from the connected sensors and are not configurable. The sensor inputs are updated in a given control cycle interval specified by the user through activation of the *Configure Control Interval* action.

5.1.3.4 Manage specifications
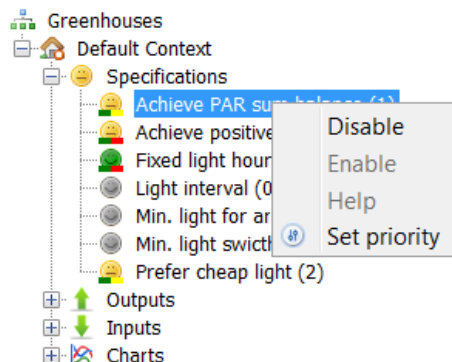
Figure 9. Configuration of Control Specifications.

There are two types of specifications: Cost and Constraints. The specification nodes have different smiley icons dependent on their type. A cost specification has green and yellow icons, constraint specifications have green and red icons. The cost specifications are formulated as objective minimization functions – i.e., the *Prefer Cheap Light* specification is a cost function that minimizes the electricity price of a sup-

plemental light plan based in electricity price forecasts. The constraint specifications are formulation as constraints that always have to be fulfilled – i.e., the *Heating Limits* specification is a constraint that ensures that the *Indoor Temperature* (*TempIn*) always stays within max/min boundaries.

Furthermore, specification smileys have different colors dependent on the found solution or if it is disabled. Disabled specifications have a grey color. A cost specification is green if the found solution fully satisfies the specification or else it is displayed in yellow. A constraint specification is green if the solution was accepted or else it is red. The specification top node displays a colored icon depicting the color and icon of the most dissatisfied specification. For example, in Figure 9 the top node is displayed as a yellow smiley because the cost specifications can only be partially satisfied as a consequence of a trade-off between the *Prefer Cheap Light* and *PAR Light Sum Balance* specifications. PAR is an abbreviation of Photosynthetically Active Radiation, which designates the spectral range (wave band) of solar radiation from 400 to 700 nanometers that photosynthetic organisms are able to use in the process of photosynthesis.

The actions for constraint and cost specifications are *Disable*, *Enable,* and *Help*. On activation of the *Help* action, the help system will open and display the help text for the selected specification node. Additionally, cost specification nodes have a priority level action to configure the priority level of the specification. For example, in Figure 9 the *Prefer Cheap Light* specification has a priority level equal to two as indicated by the number in parentheses.

5.1.3.5   Manage outputs
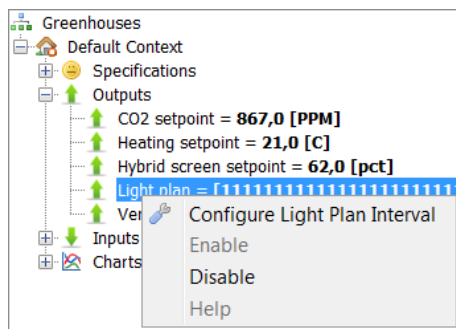
Figure 10. Configuration of Light-Plan (LightPlan) output.

Outputs can be configured from the *Outputs* node in the navigation three for each greenhouse. In Figure 10, the Light-Plan (*LightPlan*) output is configured by right clicking the specific output node. Context specific actions can be provided for specialized outputs. For example, the Light-Plan (*LightPlan*) output is a specialized output that has a context specific *Configure Light-Plan Interval* action. The common context actions for all outputs include *Enable*, *Disable,* and *Help* actions.

5.1.3.6   Output help messages
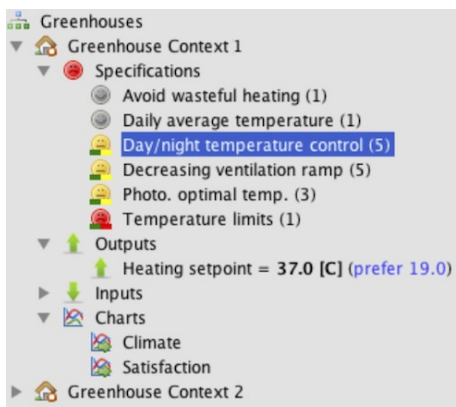
Figure 11. Output help message.

To support explanation of why a specification is dissatisfied the user can click on a specification and a help message will be displayed next to the related output. The help message expresses what the specification would have preferred compared to what is actually achieved. For example, the help message "prefer 19 °C" for the selected day/night temperature specification is next to the heating setpoint output (Figure 11).

5.1.3.7   Climate Graphs

Each greenhouse node has a charts node. It is possible for the user to create time series charts of all inputs and outputs by right-clicking the charts node and clicking the *Create New Chart* action provided in the node menu. A new chart node is created for each new time series chart (Figure 12). The actions for a chart node is *Open*, *Delete,* and *Rename* charts. When a chart node is double clicked, a chart main window is opened for the selected chart node. By default, a new chart window is always empty and it is up to the user to select the input and output time series to be displayed.
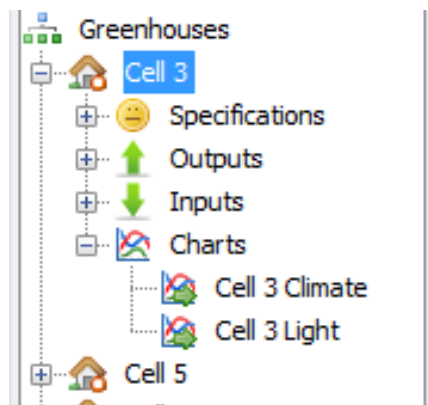
Figure 12. Climate graphs nodes in navigation tree.

Figure 13 shows the climate graph for the indoor greenhouse temperature and the indoor CO2 level. The top of the chart window has four parts: 1) a drop down box to select the number of days to be displayed, 2) date selector to select the date to display, 3) select series button to select the time series, and 4) a today button to view the graph for the system time.
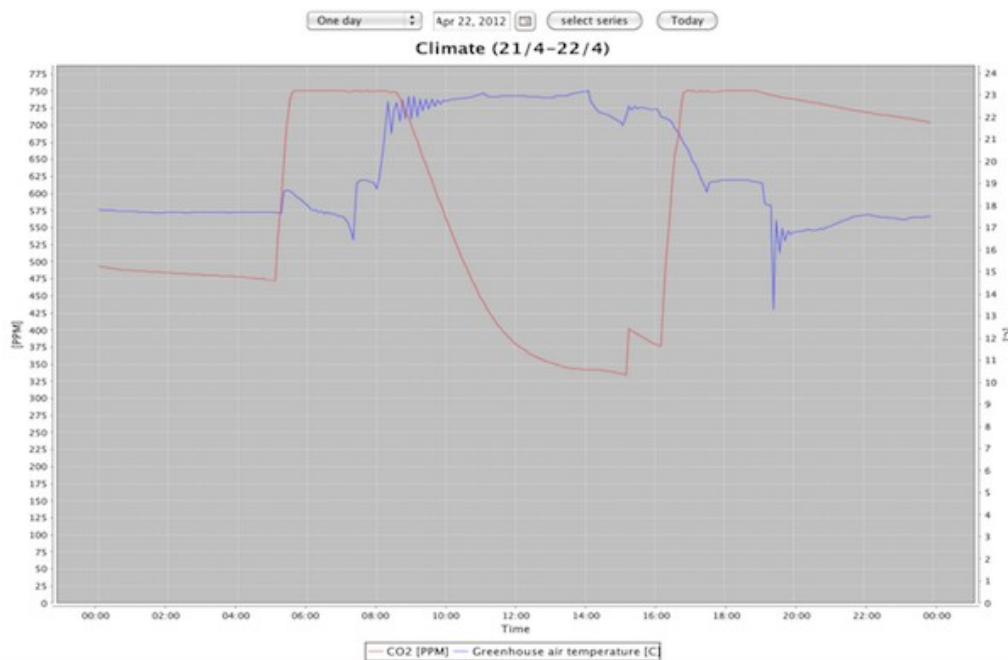
Figure 13. Climate graphs of Indoor CO$_2$ (CO$_2$) and Indoor Temperature (TempIn).

5.1.3.8 Satisficing view
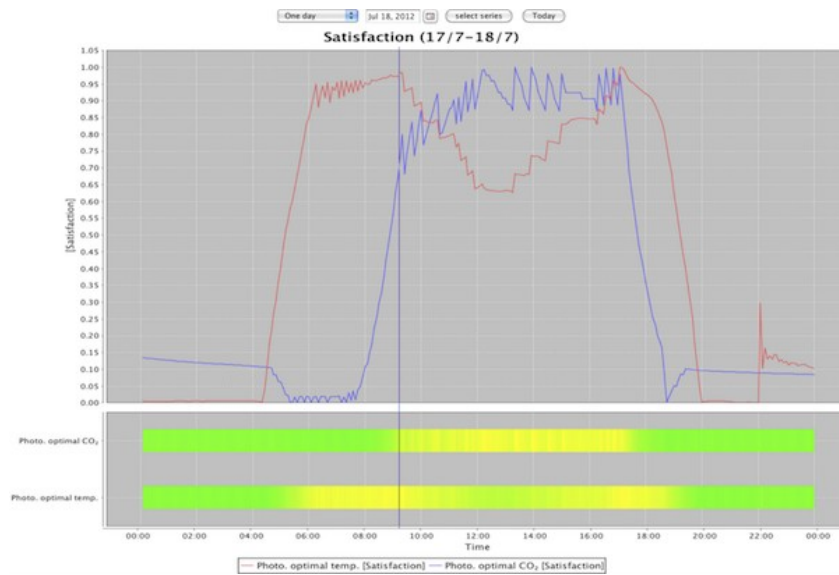
Figure 14. Satisficing view of photosynthesis optimization features.

Similar to the climate graphs, the user can create satisficing graphs for each specification by right-clicking the chart node and click the *Create New Chart* action. The satisficing graph for a specification is added by clicking the top *select series* button in the new graph window. Each satisficing graph has the same name as the corresponding specification and all has the same satisficing unit. Figure 14 shows a screen-shot of the satisficing graph for photosynthesis optimization specifications. The color bar indicates by a yellow gradient that the photosynthesis optimal temperature and CO2 level specifications are dissatisfied due the max temperature limit resulting in ventilation that compromises the goal to achieve a photosynthesis optimal temperature and CO2 level. Additionally, the dissatisfaction of the features are illustrated by the satisficing graphs. At the start of the day, both photosynthesis optimal temperature and CO2 are satisfied which is indicated by the graphs being close to the zero line. On the contrary, the dissatisficing is illustrated by the graphs getting close to the upper line (y = 1).

5.1.3.9 Graph help messages
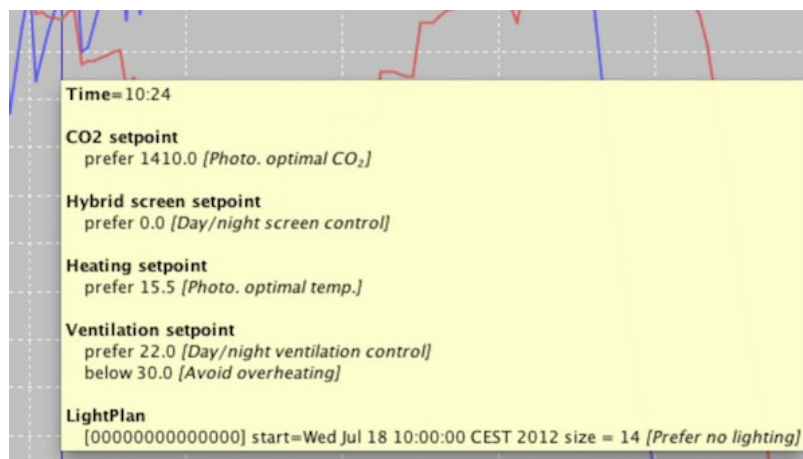
Figure 15. Specification help messages.

To get more detailed information about the state of specifications in a specific point a vertical line can be moved horizontally over the time line. As the vertical line moves across the time line help messages, provided by the specifications, are displayed for the point in time corresponding to where the vertical line is located. Figure 15 shows a screen-shot of a help message from the specifications at 10:24. A specifica-

tion provides a help message for the output it is interested in. For example, the photosynthesis optimal CO2 specification expresses in Figure 15 that it prefers a CO2 level of 1410 PPM.

5.1.3.10 Status bar
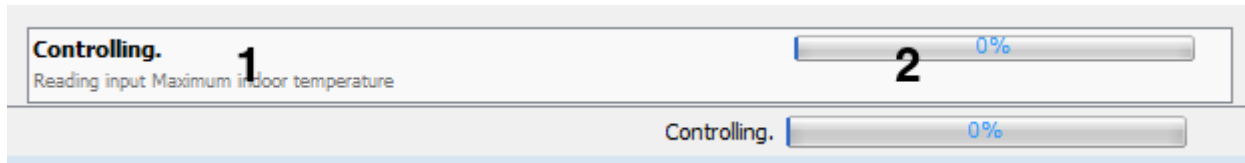
Figure 16. Status bar.

Figure 16, shows the DynaLight NG status bar that consists of two parts. The first part (1) is an information text that informs the user about the different phases of the control process that includes reading inputs, optimization, and writing of outputs. The second part (2) is a progress bar that illustrates the progress of the optimization process in percentage.

5.1.4 Control specifications

5.1.4.1 Heating
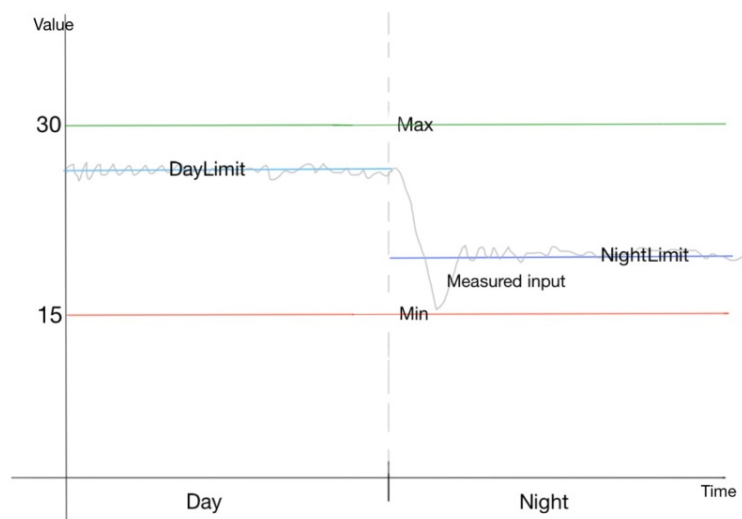
Figure 17. Different limits for day and night.

The physical water heater and a circulation pump distribute heated water through pipes to radiators that transfer the heat to the air. The heating specifications influence the heating and circulation of water to achieve a required *Indoor Temperature* (*TempIn*) in the greenhouse. The required air temperature is achieved by raising the air temperature when it drops below a certain threshold *Minimum Temp. Limit* (*TempMin*). An increase in the temperature can be achieved in various ways by issuing different air temperature thresholds specified by for example *Day Temp. Limit* (*DayTemp*) and *Night Temp. Limit* (*NightTemp*).

5.1.4.1.1 Heating limits

Inputs: Indoor Temperature (*TempIn*) [˚C], Minimum Temp. Limit (*TempMin*) [˚C], Maximum Temp. Limit (*TempMax*) [˚C].

Heating limits (SHeatLimits)
1 **return** (*HeatSp* ≥ *TempMin*) ∧ (*HeatSp* ≤ *TempMax*)

Specification: The Heating limits specification ensures that the temperature stays within acceptable boundaries – i.e. the specification imposes an upper Maximum Temp. Limit (*TempMax*) and a lower Minimum Temp. Limit (*TempMin*) for the Indoor Temperature (*TempIn*) and the Heating Setpoint (*HeatSp*), see Figure 17.

Output: Heating Setpoint (*HeatSp*) [˚C]

5.1.4.1.2 Day / night heating

Inputs: Indoor Temperature (*TempIn*) [˚C], Day Temp. Limit (*DayTemp*) [˚C], Night Temp. Limit (*NightTemp*) [˚C].

```
SHeatDayNight
1  if night
2      return absDiff(HeatSp, DayTemp)
3  else
4      return absDiff(HeatSp, NightTemp)
```

Specification: The Day/Night Heating specification influences the heating setpoint according to one threshold during the day and another during the night – i.e., the specification minimizes the absolute difference between the Indoor Temperature (*TempIn*) and Day Temp. Limit (*DayTemp*) or Night Temp. Limit (*NightTemp*) by adjusting the Heating Setpoint (*HeatSp*), see Figure 17.

Output: Heating Setpoint (*HeatSp*) [˚C]

5.1.4.1.3 Average temperature
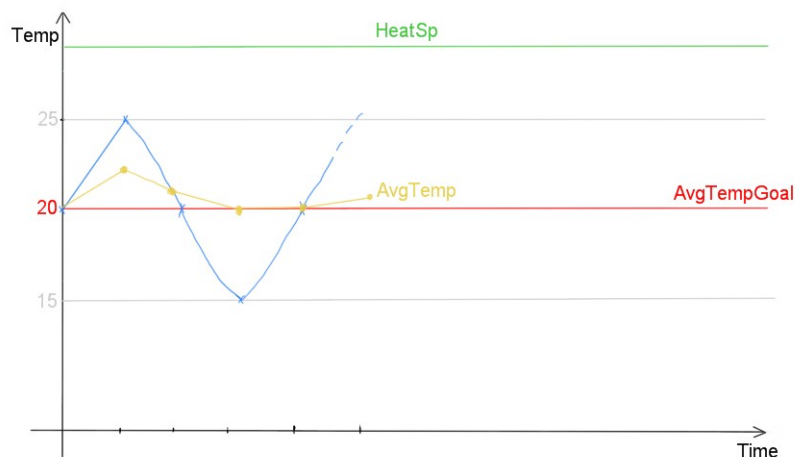
Figure 18. Average Temperature illustrated by graphs.

Inputs: Indoor Temperature (*TempIn*) [˚C], Average Temp. Goal (*AvgTempGoal*) [˚C], Average temperature (*AvgTemp*) [˚C].

```
SHeatAverage
1  return (AvgTemp ≥ AvgTempGoal) ∨ (HeatSp > AvgTempGoal)
```

Specification: The Average Temperature constraint specifies that the Heating Setpoint (*HeatSp*) is acceptable if the derived Average temperature (*AvgTemp*) at least satisfies the Average Temp. Goal (*AvgTempGoal*) or if the Heating Setpoint (*HeatSp*) is set to reach the Average Temp. Goal (*AvgTempGoal*). Figure 18 illustrates an acceptable situation where the Average temperature (*AvgTemp*) is ahead of Average Temp. Goal (*AvgTempGoal*) and the system is heating.

Output: Heating Setpoint (*HeatSp*) [˚C]

5.1.4.1.4 Photosynthesis optimal temperature

	Temperature (°C)						
	15	16	...	20	...	30	
300	1.4	1.4		2.4		1.6	
350	1.4	1.4		2.6			80 % Photo.
400	1.6	1.6		2.7	2.7	1.9	
CO₂ ...							
(PPM) ...					3.0		
1200	1.7	1.8		2.8		2.8	
...							
2000	1.7	1.9		2.9	3.2	3.0	100 % Photo.

Figure 19. The photosynthesis index at different temperatures and CO2 concentrations at a random irradiance level.

Inputs: Indoor Temperature (*TempIn*) [°C], Indoor Light Intensity (*LightIn*) [$\mu mol\ m^{-2}\ s^{-1}$], Photosynthesis Optimization Goal (*PhotoOpt*) [%]

SHeatPhoto

1 *photoDiff* = *PhotoOptTemp* − *TempIn*
2 *photoSpDiff* = *PhotoOptTemp* − *HeatSp*
3 **return** abs(*photoDiff* + *photoSpDiff*)

Specification: The photosynthesis optimal temperature specification favors a temperature that promotes photosynthesis – i.e. the specification guides the Heating Setpoint (*HeatSp*) towards a Photosynthesis Optimal Temp. (*PhotoOptTemp*) that maximizes photosynthesis. A matrix of photosynthesis indexes are calculated using a photosynthesis model, the Indoor Light Intensity (*LightIn*) and a range of CO2 levels and temperatures[1]. Figure 19 illustrates an example of a photosynthesis index matrix. The maximal photosynthesis is the largest figure and equal to 100%. The matrix is scanned to find a photosynthesis rate that fits the Photosynthesis Optimization Goal (*PhotoOpt*) chosen. The temperature level and CO2 concentration are read and used as set points. A set point of 100% secures a high photosynthesis, but energy consumption is large and the plants might be long and thin. A more reasonable set point has proved to be between 80% and 90% of the optimal photosynthesis. In the example, the index with the photosynthesis rate 2.6 is selected based on the given Indoor Light Intensity (*LightIn*) and the Photosynthesis Optimization Goal (*PhotoOpt*). The Photosynthesis Optimization Goal (*PhotoOpt*) is set to 80 % of the optimal photosynthesis rate and the resulting Photosynthesis Optimal Temp. (*PhotoOptTemp*) is then 20 °C. Depending on the Indoor Light Intensity (*LightIn*), the temperatures can vary from 15 °C to 30 °C and the CO2 concentrations from 350 to 2000 PPM.

Output: Heating Setpoint (*HeatSp*) [°C]

5.1.4.2 CO2

Plants that grow fast can quickly consume the natural ambient CO2 concentration (300-400 PPM). A low CO2 concentration lead to poor growth conditions of the crop. To avoid low CO2 concentrations the greenhouse is equipped with a CO2 doser. The required CO2 level is obtained by dosing CO2 when the actual Indoor CO2 (*CO2*) level drops below a required threshold. The CO2 specification influences the CO2 Setpoint to obtain a required CO2 level.

The Day CO2 Limit (*DayCO2*) is set to 750 PPM and Night CO2 Limit (*NightCO2*) is configured to 350 PPM. Furthermore, Minimum CO2 Limit (*CO2 Min*) and Maximum CO2 Limit (*CO2 Max*) is correspondingly set to 1500 PPM and 300 PPM.

---

[1] Oliver Körner and K. L. Nielsen. A Simple Kalanchoe Photosynthesis Model for Greenhouse Climate Control. Acta Horticulturae, 952:111-118, 2012.

5.1.4.2.1   CO2 Limits

Inputs: Minimum CO2 Limit (*CO2 Min*) [PPM], Maximum CO2 Limit (*CO2 Max*) [PPM]

SCOLimits
1 **return** $(CO_2 \, Sp \geq CO_2 \, Min) \land (CO_2 \, Sp \leq CO_2 \, Max)$

Specification: CO2 Limits ensure that the CO2 level stays within acceptable boundaries – i.e. a specification that enforces an upper Maximum CO2 Limit (*CO2 Max*) and lower Minimum CO2 Limit (*CO2 Min*) of the CO2 Setpoint. This is similar to the temperature limits in Figure 17.

Output: CO2 Setpoint [PPM]

5.1.4.2.2   Day / night CO2

Inputs: Indoor CO2 (*CO2*) [PPM], Day CO2 Limit (*DayCO2*) [PPM], Night CO2 Limit (*NightCO2*) [PPM]

SCODayNight
1 **if** *night*
2   **return** abs$(CO_2 \, Sp - DayCO_2)$
3 **else**
4 **return** abs$(CO_2 \, Sp - NightCO_2)$

Specification: The day/night CO2 specification desires different CO2 limits for day and night – i.e., a specification that   minimizes the difference between Indoor CO2 (*CO2*) and Day CO2 Limit (*DayCO2*) or Night CO2 Limit (*NightCO2*) by controlling the CO2 Setpoint.

Output: CO2 Setpoint [PPM]

5.1.4.2.3   Photosynthesis optimal CO2

Inputs: Indoor CO2 (*CO2*) [PPM], Indoor Light Intensity (*LightIn*) [$\mu mol \; m^{-2} \, s^{-1}$], Photosynthesis Optimization Goal (*PhotoOpt*) [%]

SCOPhoto
1 *photoDiff = PhotoOptCO2 - CO$_2$*
2 *photoSpDiff = PhotoOptCO2 - CO$_2$ Sp*
3 **return** abs(*photoDiff + photoSpDiff*)

Specification: The photosynthesis optimal CO2 specification favors a CO2 level that promotes photosynthesis – i.e. the strategy guides the CO2 setpoint towards a value that maximizes photosynthesis. The photosynthesis matrix described in Figure 19 is used to find the Photosynthesis Optimal CO2 (*PhotoOptCO2*) level based on the Photosynthesis Optimization Goal (*PhotoOpt*) and the measured Indoor Light Intensity (*LightIn*).

Output: CO2 Setpoint [PPM]

5.1.4.3   Screen

The screen control feature controls the screen by setting screen positions, in form of electrical pulses, to the screen step motor. The screens are configured to be folded during night and day. That is, by default the Day Screen Limit (*DayScreen*) and Night Screen Limit (*NightScreen*) are set to zero and the Maximum Humidity (*HumMax*) is set to 90 %.

5.1.4.3.1   Photo. Optimal screen

Inputs: Screen Photo. Ratio (*ScrnPhotoRatio*) [%], Outdoor Light Intensity (*LightOut*) [Wm^{-2}], Greenhouse Light Transmission Factor (*GHLightTrans*) [%], Indoor Temperature (*TempIn*) [$^{\circ}$C] and Indoor CO_2 (*CO$_2$*) [PPM]

SScrnPhoto

1   **if** isMinimiumPhotosynthesisAchieved()$_\wedge$
5   isPhotoLostWithScreens())
9   *cost = ScreenSp*
10 **else** *cost =* abs(*ClosedPos − ScreenSp*)
11 **return** *cost*

isMinimiumPhotosynthesisAchieved

2   *parWithoutScreens =* **f**romSunToPAR(*LightOut* $\times$ *GHLightTrans*)
3   *photoWithoutScreens =* calcPhoto(*TempIn*, *CO$_2$* , *parWithoutScreens*)
4   **return** *photoWithoutScreens* > MinPhotoLevel

isPhotoLostWithScreens

6   *photoWithScreens =* calcPhoto(*TempIn*, *CO$_2$* , *parWithScreens*)

7   *preservedPhotoPct* = photoWithScreens / photoWithOutScreens
8   **return** *preservedPhotoPct* > *ScrnPhotoRatio*

Specification: The Photo. Optimal Screen specification promotes not using the screens whenever there is a potential for a higher photosynthesis rate, even though the energy balance might be negative. The Photo. Optimal Screen specification minimizes the Hybrid Screen Setpoint (*ScreenSp*) (unfold the screens) when there is extra photosynthesis to be gained by the natural light. The isMinimiumPhotosynthesisAchieved() function calculates the photosynthesis rate without screens based on a photosynthesis model[2]. If the photosynthesis rate is above a minimum level the isMinimiumPhotosynthesisAchieved() function returns true (Line 3-4). The function isPhotoLostWithScreens(), calculates the ratio preservedPhotoPct between photoWithScreens and photoWithoutScreens based on the photosynthesis model to determine if the photosynthesis rate is negatively affected by pulling the screen (Line 7). The calculated ratio is compared to the Screen Photo. Ratio (ScrnPhotoRatio) input from the user. If there is a loss of photosynthesis rate by pulling the screens and a minimum level of photosynthesis is achieved then drawing back the screens is preferred (Line 9). In other cases pulling the screens is preferred to preserve energy.

Outputs: Hybrid Screen Setpoint (*ScreenSp*) [%]

5.1.4.3.2   Day / night screens

Input: Hybrid Screen Position (*ScrnPos*) [%], Day Screen Limit (*DayScreen*) [%], Night Screen Limit (*NightScreen*) [%].

SScrnDayNight

1   **if** *night*
2   **return** abs(*ScreenSp − DayScreen*)
3   **else**
4   **return** abs(*ScreenSp − NightScreen*)

Specification: The Day/Night Screen specification influences the screen according to different limits specified for day and night – i.e. the specification minimizes the absolute difference between the Hybrid

---

[2] Oliver Körner and K. L. Nielsen. A Simple Kalanchoe Photosynthesis Model for Greenhouse Climate Control. Acta Horticulturae, 952:111–118, 2012.

Screen Position (*ScrnPos*) and Day Screen Limit (*DayScreen*) or Night Screen Limit (*NightScreen*) by adjusting the Hybrid Screen Setpoint (*ScreenSp*).

Output: Hybrid Screen Setpoint (*ScreenSp*) [%]

5.1.4.4   Ventilation

The ventilation control feature influences the air temperature in a greenhouse by opening and closing the greenhouse windows. The idea behind the feature is to open a window when the air temperature reaches a maximum setpoint and to close it when it nears the wanted threshold.

5.1.4.4.1   Day/Night windows

Inputs: Indoor Light Intensity (*LightIn*) [$\mu mol\ m^{-2}\ s^{-1}$], Day Ventilation Temp. (*DayVent*) [°C] and Night Ventilation Temp. (*NightVent*) [°C]

SWinDayNight
1 **if** *night*
2   **return** abs(*VentSp − DayVent*)
3 **else**
4   **return** abs(*VentSp − NightVent*)

Specification: The Day/Night Windows specification influences the ventilation setpoint according to one limit during the day and another during the night – i.e. a satisfy function minimizes the absolute difference between Ventilation Setpoint (*VentSp*) and the limit Day Ventilation Temp. (*DayVent*) or the limit Night Ventilation Temp. (*NightVent*).

Output: Ventilation Setpoint (*VentSp*) [%]

5.1.4.5   Supplementary artificial lighting

5.1.4.5.1   PAR light sum balance

Inputs: PAR Day Light Integral (*ParDLI*) [mol m^{-2}], PAR Integral Today and Past Two Days) (*ParHist*) [mol m^{-2}], Expected Natural PAR Sum Remaining Day and Future Two days (*ParFuture*) [mol m^{-2}], Installed Lamp PAR (*LampPAR*) [$\mu mol\ m^{-2}\ s^{-1}$].

SParBal
1 *LightPlanSum =* calcPARSum(*LightPlan, LampPAR*)
2 *balance = 5 x ParDLI − (ParHist + ParFuture + LightPlanSum)*
3 **return** *balance*

Specification: The PAR Light Sum Balance specification is a cost function that minimizes a light sum balance, see Line 2. The balance is calculated over a five day time-window defined by current day, two days in the past, and two days in the future. The PAR Day Light Integral (*ParDLI*) user input specifies the goal to be achieved over the five day period. The total light-plan PAR sum (*LightPlanSum*) is calculated based on the Installed Lamp PAR(*LampPAR*) and the number of suggested light intervals in *LightPlan*. The balance is then calculated as the difference between the provided goal and the total of *ParHist*, *ParFuture,* and *LightPlanSum*.
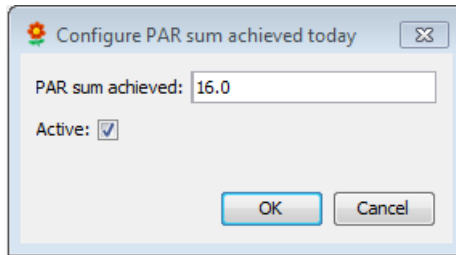
Figure 20. Configuration dialog of ParHist.

Figure 20 illustrates the configuration dialog of the *ParHist* input. The *ParHist* input is a derived input that calculates PAR integral for the current day and the past two days. In case of no historical data, the *"Active"* check-box can be unchecked and a constant for the PAR integral can be provided in the *"PAR sum achieved"* text field. When the *"Active"* check-box is checked then the PAR integral will be calculated based on the available historical data.

Output: Light-Plan (*LightPlan*) [ON/OFF].

5.1.4.5.2   Prefer cheap light

Inputs: El. Spot and Prognosis Prices (*ElCompPrices*) [EUR/MWh], Installed Lamp Effect (*InstLampEffect*) [Wm^{-2}], Greenhouse Size (*GreenhouseSize*) [m^2], and Light-Plan Time Slot (*LpTimeslot*) [h].

SCheapLight
1 return $return \sum_{i=1}^{n} LightPlan.Switch(i) * ElForecasts.Price(i) * TotalLoad * LpTimeslot(i)$

Specification: The Prefer Cheap Light specification is specified as a cost function that minimizes the price of the Light-Plan (*LightPlan*) based on El. Spot (Nord Pool spot) and Prognosis Prices (*ElCompPrices*). The Total Lamp Load (*TotalLoad*) is calculated as the Installed Lamp Effect (*InstLampEffect*) multiplied by the Greenhouse Size (*GreenhouseSize*). The index i is the time-slot index of *LightPlan*. For each light time-slot i, the sub-cost is calculated as the Total Lamp Load (*TotalLoad*) multiplied by the light-plan time-slot interval T_i and the electricity price *ElForecasts.Price$_i$*. The total cost of the Light-Plan (*LightPlan*) is then the sum of all the sub-costs for each of the light intervals *LightPlan.Switch$_i$*. The *LightPlan.Switch$_i$* is zero for light switched off and one for on.

Output: Light-Plan (*LightPlan*) [ON/OFF].

5.1.4.5.3   Fixed light hours

Inputs: Fixed Light-plan (*FixedLightPlan*) [ON/OFF].

Figure 21. Configure fixed light intervals.

SLightFixed
1 **for** $i = 0$ **to** *LightPlan.length*
2   *lightStatus = LightPlan[i]*
3   *reqStatus = FixedLightPlan[i]*
4   **if** ((*reqStatus.isOn == lightStatus.isOff*) $\vee$
              (*reqStatus.isOff == lightStatus.isOn*))
5   *misMatch = misMatch + 1*
6 **return** *misMatch*

Specification: For each timeslot *i* in the Light-Plan (*LightPlan*), the status *reqStatus* from the Fixed Light-plan (*FixedLightPlan*) and the *lightStatus* from the Light-Plan (*LightPlan*) is compared. If there is a status mismatch between a timeslot in *FixedLightPlan* and *LightPlan* then the counter *misMatch* is increased. The Fixed Light Hours specification is then expressed as a cost function that minimizes the total status mismatch *misMatch* between the *FixedLightPlan* and the proposed *LightPlan*. That is the Fixed Light Hours specification ensures that the lamps are lit in fixed number of light time intervals. A Fixed Light-plan (*FixedLightPlan*) is configured by the user and Figure 21 shows the user interface dialog for configuring the Fixed Light-plan (*FixedLightPlan*). The Fixed Light-plan (*FixedLightPlan*) is configured for a day. The number of intervals in the Fixed Light-plan (*FixedLightPlan*) is determined by the intervals specified by the Light-Plan Time Slot (*LpTimeslot*) input. For example, in Figure 21 the *LpTimeslot* is set to an hour and for that reason the daily *FixedLightPlan* has 24 time-slot intervals. Each of the intervals can be configured to be OFF (Grey), ON (yellow) or N/A (white). Intervals configured to be OFF will be switched off in the optimized Light-Plan (*LightPlan*). Likewise, intervals set to ON will be lit in the Light-Plan (*LightPlan*). The Intervals set to N/A will be flexible and can be optimized by other specifications, e.g., the Prefer Cheap Light specification can influence all the N/A intervals.

Output: A Light-Plan (*LightPlan*) that accounts for the required ON and OFF specified in the *FixedLightPlan* input.

5.1.4.5.4 OpenADR Light

Inputs: OpenADR Light Plan (OpenADRLightPlan) [ON/OFF].

```
SOpenADR
1  for i = 0 to LightPlan.length
2      lightStatus = LightPlan[i]
3      reqStatus = OpenADRLightPlan[i]
4      if ((reqStatus.isOn == lightStatus.isOff) ∨
            (reqStatus.isOff == lightStatus.isOn))
5          misMatch = misMatch + 1
6  return misMatch
```

Specification: The OpenADR Light Demand Response specification resembles that of Fixed Light Hours in section 5.1.4.5.3. The only difference is the input, which obtains information on on/off/NA lights hours through the OpenADR service in section 5.1.6.4.

Output: Light-Plan (LightPlan) [ON/OFF].

5.1.4.6 Ramping

The inherent inertia of the heater, CO2 doser, windows, and screen requires the corresponding setpoints not to change too rapidly. The ramp specification ensures that *CO2 Sp*, *HeatSp*, *VentSp,* and *ScreenSp* setpoints do not change too rapidly – i.e., accept functions for each setpoint that only accept a ramped setpoint allowing a specified amount of change per time unit.

5.1.5   Drivers for climate control computers

(a) Protocol Drivers.

(b) Library Drivers.
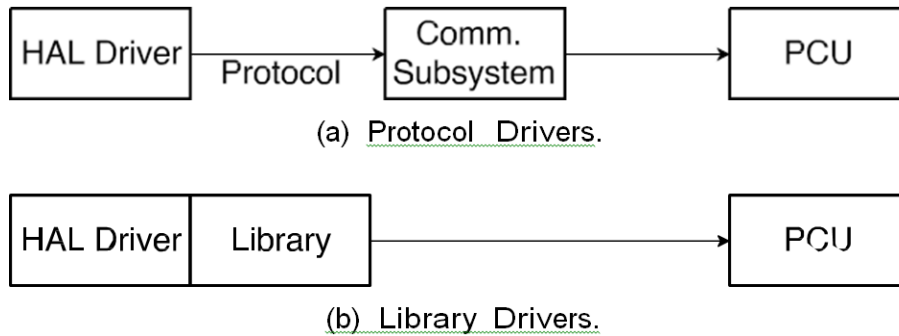
Figure 22. Driver types

The HAL driver plug-ins provide a software interface to process control units (PCUs), enabling DynaLight NG to access hardware functions without needing to know precise details of the hardware being used. A driver communicates with the PCU through a routine library or communication subsystem to which the hardware connects (Figure 22). Protocol drivers are distributed and can access the PCUs via a communication subsystem. Library drivers are based on local native libraries and have to be installed on the specific operating system. When DynaLight NG invokes a method in the driver, the driver issues commands to the device. Once the device sends data back to the driver, the driver may invoke routines in the original calling program. Drivers are hardware dependent and can be operating-system-specific.

5.1.5.1   Senmatic
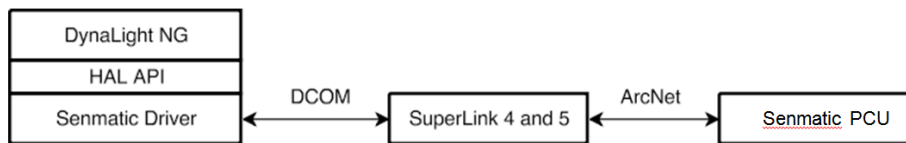
Figure 23. Context diagram of Senmatic Protocol Driver.

DynaLight NG can be connected to one or more central PCs through the Senmatic SuperLink central control program. SuperLink makes it easy and quick to read and adjust the conditions in the various greenhouse departments. DynaLight NG can operate in the same network as Senmatic Completa and DGT-Volmatics 900 PCUs and can share data with the other units in the network. Based on SuperLink it is possible to control the climate in due time with programmable control instructions. All necessary measurements are collected and saved as preferred by the user. Figure 23 illustrates the context diagram of the Senmatic Driver. The Senmatic Driver is implemented as a plug-in in DynaLight NG using the HAL API and can be replaced by other third party implementations. The DCOM network protocol[3] is used by the Senmatic Driver to connect to the remote Senmatic SuperLink system. The SuperLink system is used by DynaLight NG to read and write variables to/from the connected PCUs. Senmatic SuperLink 4 and 5 communicates with the connected Senmatic PCUs using the ArcNet protocol[4].

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[3] Microsoft. Distributed Component Object Model.   https://technet. microsoft.com/en-us/library/cc958799.aspx.

[4] ARCNET Trade Association (ATA). A Network for an Attached Resource Computer (ARCNET). http://www.arcnet.com.
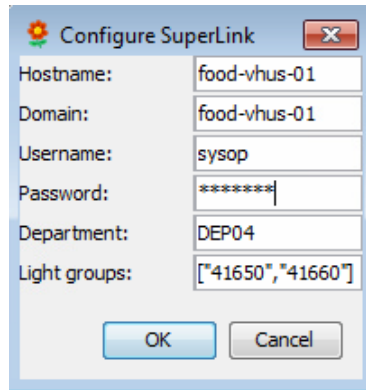
Figure 24. Configure Senmatic Driver.

DCOM has to be configured, to establish the communication link between DynaLight NG and Senmatic SuperLink (Figure 23). The DCOM configuration has to be configured both on the client and server side. DynaLight NG acts as a client and the SuperLink system act as a server. Figure 24 shows the dialog-box for the "Configure SuperLink" action for DynaLight NG. The client properties that can be entered by the user are described in Table 1:

Property	Description
Hostname	Address of the host where the COM object resides. This should be in the IEEE IP format (e.g. 192.168.170.6) or a re-solvable HostName.
Domain	Domain of the DCOM user.
Username	Name of the DCOM user.
Password	Password of the DCOM user.
Department	SuperLink ID of the greenhouse department.
Light groups	SuperLink codes for supplemental light groups. Multiple light groups can be entered using the comma separator. All entered codes for light groups will be controlled by Dy- naLight NG

Table 1. DCOM and SuperlLink DynaLight NG configuration.

The Senmatic implements the HAL API that maps control input and output to Senmatic codes using a property file, see Listing 1.

```
# Input
IndoorTemperature = 41001
OutdoorTemperature = 55
CO2 = 41014
IndoorLightIntensity = 51017
Humidity = 41015
OutdoorLightIntensity = 56
WindowOpening = 41006
SuppLightStatus = ${light.groups}
# Output
HeatingSetpoint = 41102
VentilationSetpoint = 41303
CO2Setpoint = 41610
ScreenPosition = 41535
LightSetpoint = ${light.groups}
```

Listing 1. HAL configuration file for the Senmatic Driver.

To grant DynaLight NG access to the SuperLink system via DCOM, access rights has to be configured on the SuperLink Windows PC. The OPC server configuration described in the linked documentation is similar for the SuperLink DCOM server. For further information about granting DCOM access rights on a DCOM Windows OPC server[5].

5.1.5.2 PRIVA

Figure 25. Context diagram of PRIVA POSYS Library Driver.

Figure 25 illustrates the context of the PRIVA Driver. The PRIVA Driver is implemented on top of the Priva Open SYStems API (POSYS). POSYS is a set of routines available for the application programmer to read variables on an Int´egro PCU and can for example be used to develop a user interface or a data logger. The POSYS API is developed to be able to write applications that are PCU software version independent. In this way it is not necessary to change an application each time a new version of the PCU software is released. The POSYS API is available as a Microsoft Windows posysx32.dll (16- and 32 bits). The 16 bits DLL can be used under Windows by 16 bits Windows applications and under MSDOS by MSDOS 16-bits. The 32 bits DLL can be used by Win32 applications. Note, that the posysx32.dll is pre-installed at the PRIVA Office Direct Server and the PRIVA Driver has to access this DLL and for that reason need to be installed at the same machine as PRIVA Office Direct. Alternatively, the DLL can be configured to be accessible through the DCOM protocol but it requires more setup of the server-side. The DCOM setup is at present time not supported by the PRIVA Driver.

Description	Range	Example
Category Identifier	I or M	M
Category Number	1-9999	100
Category Depth Number	0-9	0
Category Index Identifier	N	N
Category Index	0-9999	1
Line Identifier	R	R
Line Index	0-9999	2
Variable Identifier	V	V
Variable Number	1-999	1

Table 2. SCAD Syntax for Indoor Temperature (TempIn).

The POSYS API uses a SCreen ADdress, a SCAD, to address a variable on the PCU. A SCAD is a sequence, a string, of ASCII characters that addresses a variable in the CUI. Note that this addressing mechanism restricts the POSYS API to only access variables that are made available by the character user interface (the CUI). The syntax of the Indoor Temperature (TempIn) SCAD is illustrated in Table 2 and is written in a string format as "M100.0N1R2.1V1".

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[5] TAKEBISHI. DCOM Configuration. http://www.faweb.net/us/opc/dcom.html.
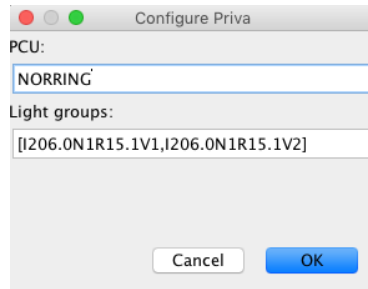
Figure 26. User configuration dialog-box of PRIVA Driver.

Figure 26 depicts the DynaLight NG dialog-box for the "Configure Driver" action. The user enters the identifier of the PCU in the "PCU" text-field. Additionally, supplemental light group SCADS can be entered in a JavaScript Object Notation (JSON) list format in the "Light groups" text-field.

```
# Input
IndoorTemperature = M100.0N1R2.1V1
OutdoorTemperature = M100.0N1R1.1V1
CO2 = M100.0N1R2.1V4
IndoorLightIntensity = M100.0N1R3.1V6
Humidity = M100.0N1R2.1V2
OutdoorLightIntensity = M4.0N1R6.1V2
WindowOpening = M125.0N1R9.1V1, M125.0N1R18.1V1
SuppLightStatus = I206.0N1R15.1V1, I206.0N1R15.1V2, I206.0N1R15.1V3, I206.0N1R15.1V4
# Output
HeatingSetpoint = M110.0N1R4.1V1
VentilationSetpoint = I120.0N1R5.1V1
CO2Setpoint = M100.0N1R2.1V4
ScreenPosition = I168.0N1R8.1V1 , I168.0N1R8.1V2
LightSetpoint = I206.0N1R15.1V1 , I206.0NR15 .1V2 , I206.0N1R15.1V3 , I206.0N1R15.1V4
```

Listing 2. HAL configuration file for the PRIVA Driver.

The PRIVA Driver implements the HAL API and maps DynaLight NG I/O to PRIVA I/O using a property configuration file. Listing 2 shows an example of a HAL I/O mapping file that maps DynaLight NG HAL variables to PRIVA SCADS.

5.1.6   Services

DynaLight NG integrates with external services through specialized service inputs – e.g., data services like outdoor light forecast and electricity price prognosis are provided by the Outdoor Light Forecast (*OutLightFuture*) service input and the Electricity Price Prognosis (*ElPriceProg*) service input. Inputs that uses external services include: Expected Natural PAR Sum Remaining Day and Future Two days (*ParFuture*), El. Spot and Prognosis Prices (*ElCompPrices*), Electricity Spot Prices (*ElSpotPrices*), Electricity Price Prog- nosis (ElPriceProg), Outdoor Light Forecast (*OutLightFuture*), and OpenADR Light Plan (*OpenADRLightPlan*). The outdoor light forecast services implement the same *WeatherService* service provided interface and can be exchanged. By default the DynaLight NG will be installed with the ConWx service provider[6]. The electricity price services implement the same *EnergyPriceService* service provided interface. DynaLight NG can be configured to use different service providers but by default the electricity price services are provided by Nord Pool[7].

---

[6] ConWx. ConWx Intelligent Forecasting Systems. http://conwx.com.

[7] Nord Pool. Nord Pool Electricity Spot Prices. http://www.nordpoolspot.com.

5.1.6.1 ConWx weather forecasts

Efficient dynamic lighting control is strongly dependent on the quality of the weather forecast. ConWx is the project partner responsible for delivering weather forecasts. As part of the project ConWx has primarily worked on optimizing their weather prediction model, including:

1. Cloud condensation algorithm: The relative humidity threshold for cloud creation in standard atmosphere is decreasing with altitude from 95 % to 75 % in the model in order to simulate grid scale clouds effects. This configuration effectively eliminates clouds from PBL, but produce challenges in situations with fog. Because of that, the algorithm for humidity threshold has been changed to include atmospheric stability and wind speed (to eliminate problem with high stability and when wind is stronger than 2 m/s). The new algorithm can decrease relative humidity threshold near ground in regions with high inversion and no wind at 75 % and produce fog or low clouds near ground.

2. Radiation code: An algorithm for optical cloud depth has been implemented using the same logic like for the relative humidity threshold and cloud optical depth can be almost 4 times higher in regions where strong inversion connected with very low wind exists. This change ensures that in winter fog can stay near ground all day and produce very near reality cloud cover and temperature.

3. Vertical diffusion of clouds: The model has had a problem with vertical diffusion that spread cloud water below or up from clouds too easy and produce regions with too dense cloud cover. In vertical diffusion the cloud water mixing ratio have been removed and instead the parameters temperature and specific humidity are used and in Vertical diffusion code we have switched to using liquid water potential temperature and liquid water specific humidity. This change effectively reduced problem with false stratiform clouds.

The optimization work resulted in a new weather model that improved the accuracy of predicting the solar irradiation. Accurate prediction of solar irradiation is crucial for precise optimization of the artificial lighting.

The DynaLight NG connects to the ConWx weather forecast service through a) the Outdoor Light Forecast (*OutLightFuture*) input (Figure 27). For every control interval, *OutLightFuture* input fetches data from a database containing the ConWx weather data. To fetch the data the *OutLightFuture* input looks up the service provider of the weather forecast service based on the *WeatherService* interface.
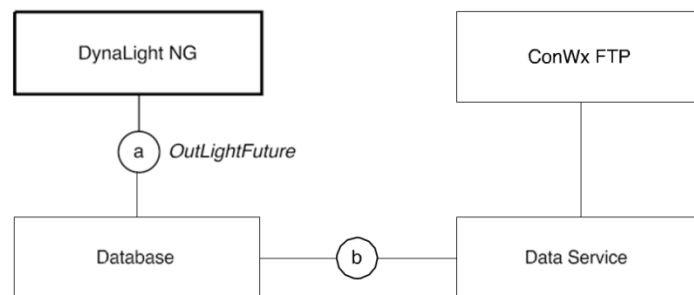
Figure 27. Context diagram of the ConWx Service.

The returned *OutLightFuture* input is location specific and the greenhouse location needs to be send as an argument to the service provider of the weather Database. To activate the *OutLightFuture* configuration input dialog-box the user right-click the *OutLightFuture* input in the navigation tree (Figure 28a). Figure 28b shows the user configuration dialog-box for the *OutLightFuture* input. The location is specified in a text-field using the following specific location codes (Table 3).

Code	Description
aarslev	"AU Aarslev", Kirstinebjergvej 10, Postboks 102, DK 5792 Aarslev

alfpedersen	"Alfred Pedersen and Son ApS", Assensvej 219, DK 5250 Odense
hjorte	"Hjortebjerg A/S", Hjortebjergvej 26, DK 5471 Snders
knudjepsen	"Queen - Knud Jepsen A/S", Skanderborgvej 193, DK 8382 Hinnerup
pkm	"PKM A/S", Slettensvej 207, DK 5270 Odense N
rosadani	"Rosa Danica A/S", Birketvedvejen 31, DK 5290 Marslev
sdu	University of Southern Denmark, Campusvej 55, DK 5230 Odense

Table 3. Location codes for the ConWx Database.
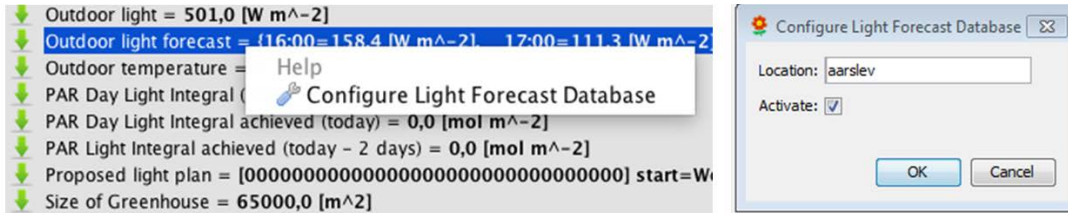
(a) *OutLightFuture* input action.   (b) *OutLightFuture* input dialog-box.

Figure 28. Configuration GUI for OutLightFuture input.

The status of the "*Activate*" check-box determines if the weather data is fetched remotely or if the latest data from the local weather database is used. If the check-box is checked then data is fetched remotely via the service provider else the latest local data is used. The ConWx weather data is provided as raw files from a FTP server and is piped into the database through a separate interface b) by a server Data Service. The Data Service fetches the raw data files in regular intervals to keep the Database updated. The Database and Data service are hosted by the University of Southern Denmark.

```
db.url=jdbc:MySQL://130.225.157.104:3306/weatherforecastconwx?autoReconnect=true
db.user=testUser
db.password=TestPass
```

Listing 3. ConWx Service Configuration File.

The *OutLightFuture* input can be configured through a configuration file but the default configuration is recommended. Listing 3 shows an example configuration file for the *OutLightFuture* input. The configuration file contains key value pairs, e.g., the username "*TestUser*" is the value of the key *db.user*. The key *db.url* defines the unique resource identified for the Database.

5.1.6.2 Energi Danmark A/S - electricity price forecasts

Electricity price forecasts from Energi Danmark A/S have been integrated together with Nord Pool spot prices. That is, the electricity price data for day ahead is the spot prices and the data for second and third day are from the Energi Danmark A/S forecast. The data from the two providers have been integrated into one combined time series. The combined electricity-price time series is used by the DynaLight NG's light control specifications to obtain a cost-effective light plan.

The integration of data from Energi Danmark A/S made it possible to move not only electricity consumption for SON-T and LED lamps from day to day, but also the production of electricity from Knud Jepsen own Combined Heat and Power plant, thereby optimizing the cost of production and consumption.

Furthermore, the Nord Pool and Energi Danmark A/S data are provided as separate time series for visualization in DynaLight NG. Last, several bug fixes for visualizing the data time series have been provided. The new Energi Danmark electricity price forecast has an effect on how commercial growers plan their production and reduce the light and temperature in periods with high level of natural light. In summary,

the longer forecast enables the commercial greenhouse growers to minimize electrical energy consumption in specific periods of the production.
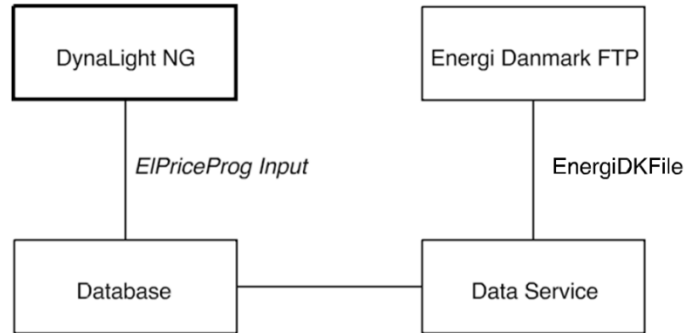
Figure 29. Context diagram of the Energi Danmark Service.

The DynaLight NG connects to the Energi Danmark A/S service through the Electricity Price Prognosis (*ElPriceProg*) input (Figure 29). For every control interval, Electricity Price Prognosis (*ElPriceProg*) input fetches data from a database containing a five-day forecast of electricity prices. To fetch the data the *ElPriceProg* input looks up the service provider of the Energi Danmark A/S service based on the *EnergyPriceService* interface.

(a) *ElPriceProg* input action. (b) *ElPriceProg* input dialog-box.

Figure 30. User configuration of ElPriceProg input.

Figure 30 shows the GUI for configuring the Electricity Price Prognosis (*ElPriceProg*). To activate the *ElPriceProg* configuration input dialog-box the user right-click the *ElPriceProg* input in the navigation tree (Figure 30a). In the *ElPriceProg* configuration input dialog-box, the user enters information about the electricity grid area (Figure 30b) and the price currency.

Price Type	Description
DK WEST	Forecast prices for the Danish electricity grid west of Storebælt
DK EAST	Forecast prices for the Danish electricity grid east of Storebælt
DK SYS	The system price for each hour is determined by the intersection of the aggregate supply and demand curves which are representing all bids and offers for the entire Nordic and Baltic region.

Table 4. Type of Prices.

The options of the El. Price Area drop-box is described in Table 4. The currency is entered in ISO 4217 format [4]. Furthermore, the a "*Activate El. Price Input*" check-box is used to enable/disable the *ElPriceProg* input. The Energi Danmark data is provided as raw files from a FTP server and is piped into the database through a separate interface by a server Data Service. The Data Service fetches the raw data files in regular intervals to keep the Database updated. The Database and Data service are hosted by the University of Southern Denmark.

```
# FTP
ftp.userid = spotprisprognoseftp.password=1234
ftp.availableServerPort=21
ftp.host=ftp1.energidanmark.dk
ftp.remote.dir=/Spotprisprognoseftp.inbound.dir=energidanmark
ftp.file = spotprisprognose.csv
# Database
jdbc.driverClassName=com.mysql.jdbc.Driver
jdbc.url=jdbc:mysql://127.0.0.1:3306/climate elpricesjdbc.username=DbUser
jdbc.password=1234
```

Listing 4. Energi Danmark Service Configuration File.

The *ElPriceProg* input can be configured through a configuration file but the default configuration is rec-ommended. Listing 4 shows an example configuration file for the *ElPriceProg* input. The configuration file contains key value pairs, e.g., the FTP username "*spotprisprognose*" is the value of the key *ftp.userid*. Table 5 describes each of the keys in the configuration file.

Key	Value
ftp.userid	Energi Danmark FTP Server Username.
ftp.password	Energi Danmark FTP Server Password
ftp.availableServerPort	Energi Danmark FTP Server Port number.
ftp.host	Energi Danmark FTP Server URL
ftp.remote.dir	Energi Danmark FTP Server remote directory where the raw data files are published
ftp.inbound.dir	The inbound directory where the Energi Danmark Service stores the fetched data files locally.
ftp.file	The file name of the raw data file to be fetched from the FTP server.

Table 5. Table describing the key/value pair of the Energi Danmark Data Service.

5.1.6.3   Nord Pool
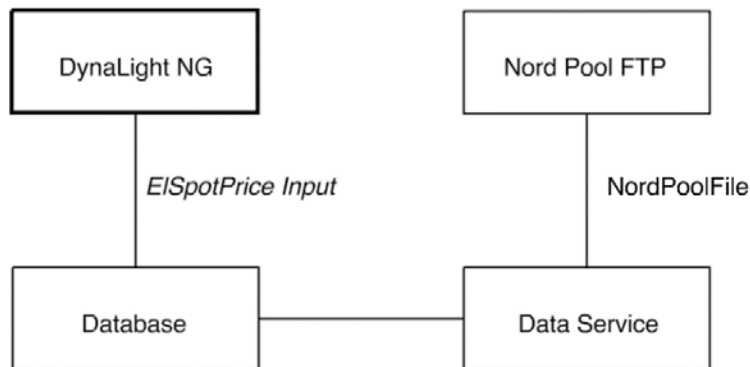
Figure 31. Context diagram of the Nord Pool Service.

The Nord Pool Service is similar to the Energi Danmark A/S service. The DynaLight NG connects to the Nord Pool service through the Electricity Spot Prices (ElSpotPrice) input (Figure 31). For every control interval, Electricity Spot Prices (ElSpotPrice) input fetches data from a database containing day-head spot electricity prices. To fetch the data the *ElSpotPrice* input looks up the service provider of the Energi Dan-mark A/S service based on the EnergyPriceService interface.

(a) *ElSpotPrices* input action.   (b) *ElSpotPrices* input dialog-box.
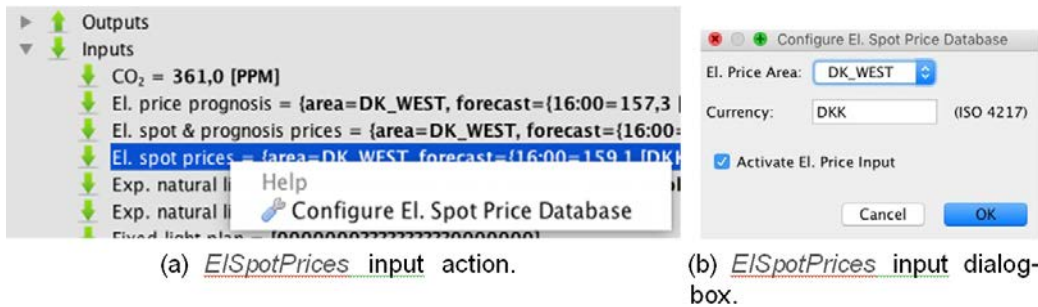
Figure 32. Configure ElSpotPrice input.

Figure 32 shows the GUI for configuring the Electricity Spot Prices (*ElSpotPrice*). To activate the *ElSpot-Price* configuration input dialog-box the user right-click the *ElSpotPrice* input in the navigation tree (Figure 32a). The *ElSpotPrice* configuration input dialog-box is similar to the *ElPriceProg* input dialog-box, the user enters information about the electricity grid area (b) and the price currency, see Section 5.1.6.2.

```xml
<?xml version="1.0" encoding="Cp852" standalone="no"?>
<!DOCTYPE properties SYSTEM " http://java.sun.com/dtd/properties.dtd">
<properties>
<!--Nordpool ftp properties-->
<entry key="NpUrl"> ftp.nordpoolspot.com</entry>
<entry key="NpUer">maersk</entry>
<entry key="NpPw">1234</entry>
<entry key="RemoteDir">Elspot/Elspot file</entry>
<entry key="SpotPrefix">spot</entry>
<entry key="SpotPostfix">.sdv</entry>
<!--Local properties-->
<entry key="LocalDir">SpotFiles</entry>
<!--Scheduler properties.-->
<entry Key="CroneExpr">0 38 11 * * ? *</entry>
<!-- "ss mm HH * * ? *"for daily at HH:mm:ss-->
<entry key="Try Again Millis">300000</entry>
<!--milliseconds to wait until another try-->
<!--Db properties-->
<entry key="DbUrl">jdbc:mysql://tek-sweat-2.mmmi.sdu.dk/climate elprices</entry>
<entry key="DbUser">erso</entry>
<entry key="DbPw">1234</entry>
</properties>
```

Listing 5. Nord Pool Service Configuration File.

The *ElSpotPrice* input can be configured through a configuration file but the default configuration is rec-ommended. Listing 5 shows an example configuration file for the *ElSpotPrice* input. The configuration file contains entry tags for key/value pairs, e.g., the FTP username "*maersk*" is the value of the <entry key="NpUser"> tag. Table 6 describes each of the keys in the XML configuration file.

Key Tag	Value
<entry key=NpUser>	Nord Pool FTP Server Username.
<entry key=NpPw>	Nord Pool FTP Server Password
<entry key=NpUser>	Nord PoolFTP Server Port number.
<entry key=NpUrl>	Nord Pool FTP Server URL
<entry key=RemoteDir>	Nord Pool FTP Server remote directory where the raw data files are published

\<entry key=LocalDir\>	The inbound directory where the Nord Pool Service stores the fetched data files locally.
\<entry key=CroneExpr\>	Unix cron expression for when the raw data files will be fetched from the FTP server.

Table 6. Table describing the key/value pair of the Nord Pool Service XML Configuration file.

5.1.6.4   OpenADR integration

OpenADR is a proposed standard specification for Demand Response (DR) signals. The OpenADR specification includes message semantics and currently supports two transport protocols namely HTTP and XMPP, the latter of which is recommended. DynaLight NG provides an implementation of the OpenADR specification in a plug-in, which enables DynaLight NG to send and receive OpenADR messages via the XMPP transport protocol. The implementation has been done using a subscriber pattern, where inputs can subscribe to OpenADR messages of specific types, in order to receive messages relevant to them. When the OpenADR plug-in receives messages via connected external parties, such as electricity service providers, these are propagated to subscribing inputs. This means, that OpenADR can be included through any Control Specification that includes inputs that subscribes to the OpenADR driver.

5.1.7   Core

The Core plug-ins include Optimization, Resources, Climate database, entity data, etc. An optimization plug-in provides an implementation of a multi- objective optimization mechanism that ensures the output of the system is an optimal trade-off of the control objectives provided by the installed Control strategies plug-ins. Different implementation of optimization plug-ins can be provided as long as the plug-in implements the specific Multi-Objective Optimization API. Only one optimization plug-in can be installed and be active at the time. The resource plug-ins handle the internationalization of JavaHelp another resources. The user can easily store text constants in property files for specific languages. The resource plug-ins loads text constants and icons applicable to the current country and language settings. Data read from sensors and actuators is continuously stored in a local embedded database in specific intervals. The intervals for storing the data is specified by the user, see "Configure Control Interval" in Subsection 3.2. The stored climate data is used internally for visualizing climate graphs over longer periods. Data types shared across DynaLight NG plug-ins are provided in the Entity plug-ins.

5.2   Smart Grid integration of greenhouse nurseries

Smart grid integration of commercial greenhouse growers covers how to use the flexibility found in a nursery for the planning of electricity consumption in relation to the variation in electricity prices. The goal is to optimize the price of the energy used in the greenhouses without compromising on the quality of plant production.

In this feasibility study, we consider a commercial greenhouse grower with its own Combined Heat and Power plant CHP, which is used for producing electricity and heat for the production of plants. Both the supply of electricity and heat is essential in order to ensure optimal growth conditions.

The project has investigated three approaches to reduce the energy costs. The first approach uses the DynaLight NG software developed by SDU, as described in section 5.1. The second uses the Power Hub technology provided by DONG Energy to optimize the operation the commercial greenhouse growers' combined heat and power plant, and the third considers the integration of the two.

5.2.1   Optimization of combined heat and power plant

As illustrated in Figure 33 the Combined Heat and Power plant (CHP) consists of a gas turbine, which produces both electricity and heat. Additionally, there is a gas boiler that only delivers heat.
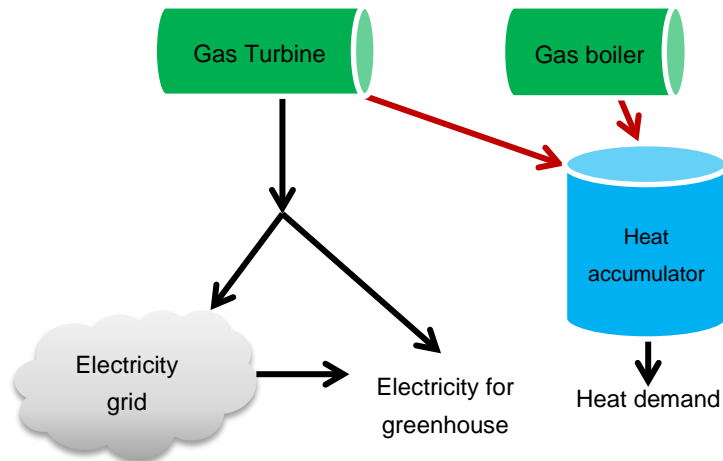
Figure 33. An outline of the combined heat and power plant

As seen from the figure there is flexibility in regards to how electricity and heat are produced. Heat can be produced on the gas turbine, as part of co-generation with electricity, or it can be produced on the gas-boiler. Furthermore, there is a heat accumulator, which allows heat to be stored for later use. This allows the heat production to be time shifted. Alternative to using the gas turbine for producing electricity, it can be purchased from the electricity spot market. Additionally, it is an option to export electricity and thereby become a net producer.

This structure of the CHP enables growers to switch between the production of heat and power, which will imply a flexibility that can be applied in the production planning of the power plant's operation. The size of the heat accumulator implies no need to know the demand for heat in detail in order to plan the production. Only electricity demand and electricity prices influence the decision.

The electricity system functions in such a way that the quantity of electricity, which has to be imported or exported is sold on the market the day before the operational day. That is, it is necessary to predict the need for electricity and heat as well as the price of electricity one day ahead.

In the investigation, work is concentrated on the fact that the electricity demand is presumed to be identified in connection with planning, and a forecast of the electricity prices is developed which is a part of what Power Hub already is able to deliver.

The CHP has been modelled in Power Hub by DONG Energy, and an operational plan for a historical period extending over one year has been made. The financial result of this simulation is shown in Figure 34. compared to the historical data, thus an increased export of power together with a significant smaller import of power has been identified. That is, there is a slightly increased production of power at the CHP plant.

Own consumption in optimization = Process only					
	QUEEN Actual	Power Hub		Difference	
				[DKK]	[%]
Total power export	7833186,17	9084052,51	kWh electricity	1250866,35	15,97
Total power export price	2108359,57	2470522,77	DKK	362163,20	17,18
Total power internal	5312388,42	6894661,88	kWh electricity	1582273,46	29,78
Total power internal cost	-507333,09	-658440,21	DKK	151107,12	29,78
Total power import	2156790,58	574516,92	kWh electricity	-1582273,66	-73,36
Total power import cost	-1178956,02	-316820,18	DKK	-862135,84	-73,13
Total engines gas consumption	-34128540,73	-41483938,31	kWh gas	7355397,58	21,55
Total engines gas cost	-9385348,70	-11408083,03	DKK	2022734,33	21,55
Total boiler gas consumption	-6518753,13	0,00	kWh gas	-6518753,13	-100,00
Total boiler gas cost	-1792657,11	0,00	DKK	-1792657,11	-100,00
Total engines heat production	15505836,05	20639705,38	kWh heat	5133869,33	33,11
Total boiler heat production	5215002,50	0,00	kWh heat	-5215002,50	-100,00
Total heat production	20720838,55	20639705,38	kWh heat	-81133,17	-0,39
Total Revenue	2108359,57	2470522,77	DKK	362163,20	17,18
Total Cost	-12864294,92	-12383343,43	DKK	-480951,50	-3,74
Netto	-10755935,35	-9912820,66	DKK	-843114,69	-7,84
Total reduction in DKK	0	843115	DKK		
Total reduction in %	0	7,84	%		

Figure 34. Results from the simulation study

When the heat production is evaluated two observations can be made. The first observation is that the total heat production is almost identical in the two scenarios. This confirms that the simulated plan meets the demand of heat in the greenhouse. The other observation is that in order to meet the heating de-mand the entire production is transferred to the gas turbine, which simultaneously produces electricity and heat. Lastly, it is worth noticing that the aggregated import of gas also increases considerably in the simulation compared to the real run in order to meet the increased production of electricity. This increase in costs, however, this is compensated by the increased turnover on export of electricity. Thus, in total a reduction in costs of approximately 8 % is achieved.

5.2.2 Combined optimisation of combined heat and power plant and growth light

Regarding combined optimization of the CHP and the use of artificial lighting there are two questions, which have to be answered. One is whether it is possible to describe the use of artificial light in a Power Hub terminology; the other case is whether it makes sense from an economic perspective.

Power Hub is modelling its optimization as a set of converting units, nodes and reservoirs. If it must be possible to optimize the use of artificial lighting and the CHP in combination, it must be possible to ex-press the need for photosynthesis as a collection of those units. It has been found possible to express this, both as a simple model and a more complex model. The simple model is shown in Figure 35.
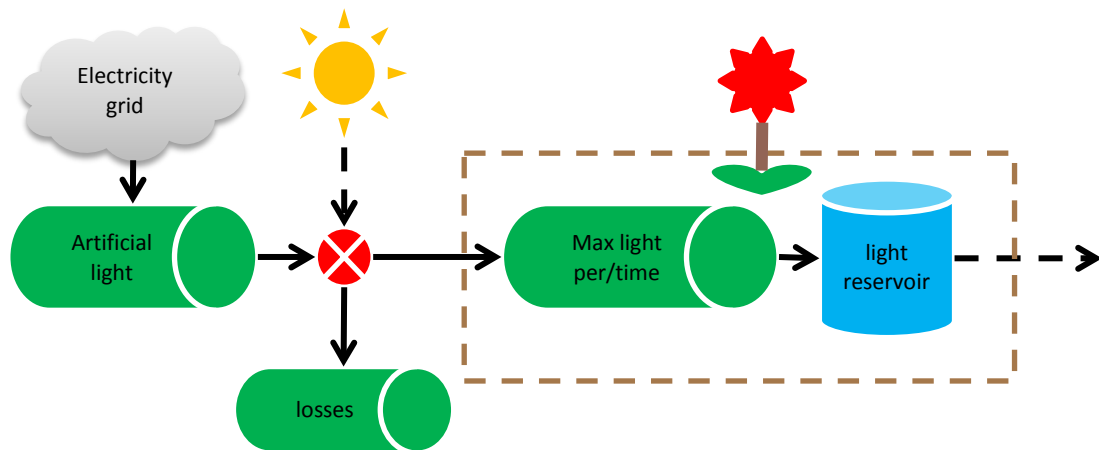
Figure 35. Growth light as a simple model

The green cylinders show the converted units, the red circle is a node, and the blue vertical cylinder is a reservoir. Starting from the right hand side, the photosynthesis need is given as a light reservoir, which has to be filed. The arrow on the right hand side is an uncontrollable disturbance, which is pulling the reservoir, and the combination of artificial light and natural light will have to fill the reservoir.

In order to meet declining effectivity of the photosynthesis process, when the light intensity increases, a converting unit is added in order to set a maximum level. The light is coming partly from the natural daylight and partly from artificial lighting. Hence, in order to plan the use of artificial lighting, it is necessary to have a weather forecast predicting the level of natural daylight.

Figure 36 illustrates a more advanced version of the photosynthesis model, in which it is statically taken into consideration that the optimal concentration of CO_2 is shifting throughout the day. Additionally, it is possible to make other similar initiatives where other factors regarding control of the artificial lighting is taken into account. Furthermore, it will be possible to make an extended integration between Power hub and DynaLight NG so that the converting curve between light and photosynthesis will be calculated by DynaLight NG as a full day varying curve and sent to Power Hub, which will take this curve into consideration when planning the use of artificial lighting. However, this indicates that it is possible to describe the process with the terminology of Power Hub, with the important requirements there are in regard to the planning of artificial light.

Tests with planning based on this model confirm that this is also possible, and the results of this indicate the same pattern as planning via DynaLight NG. However, DynaLight NG has the advantage that it includes more factors and is able to correct the use of artificial lighting during the day according to the actual daylight level.
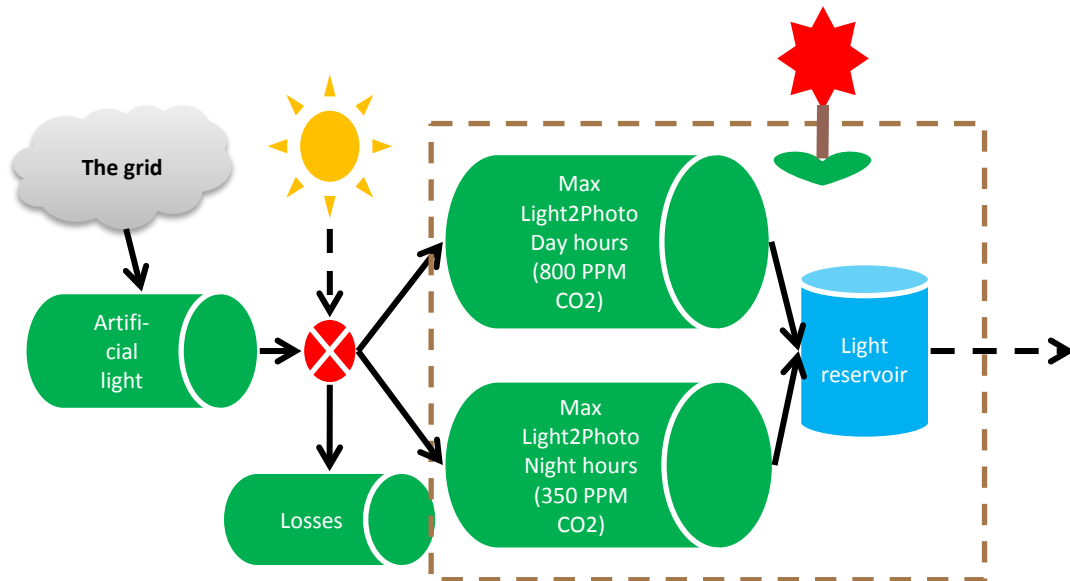
Figure 36. Advanced model of the growth light

As illustrated in Figure 37, an IT-architecture has been suggested for integrating Power Hub and Dyna-Light NG to optimize and control the CHP and the use of artificial lighting in combination. Power Hub keeps the artificial light model, described above, together with the CHP model. Power Hub exhibits a number of web services, which may be used for applying data used for planning. DynaLight NG is responsible for the physical control of the artificial lighting, measurements of the light, and all parameters necessary for controlling the greenhouse climate. Additionally it contains this kind of modelling in order to translate the physical measurements for the data of photosynthesis. These measurements are sent to Power Hub in order to make a plan for the artificial lighting, which afterwards will be executed by Dyna-Light NG.
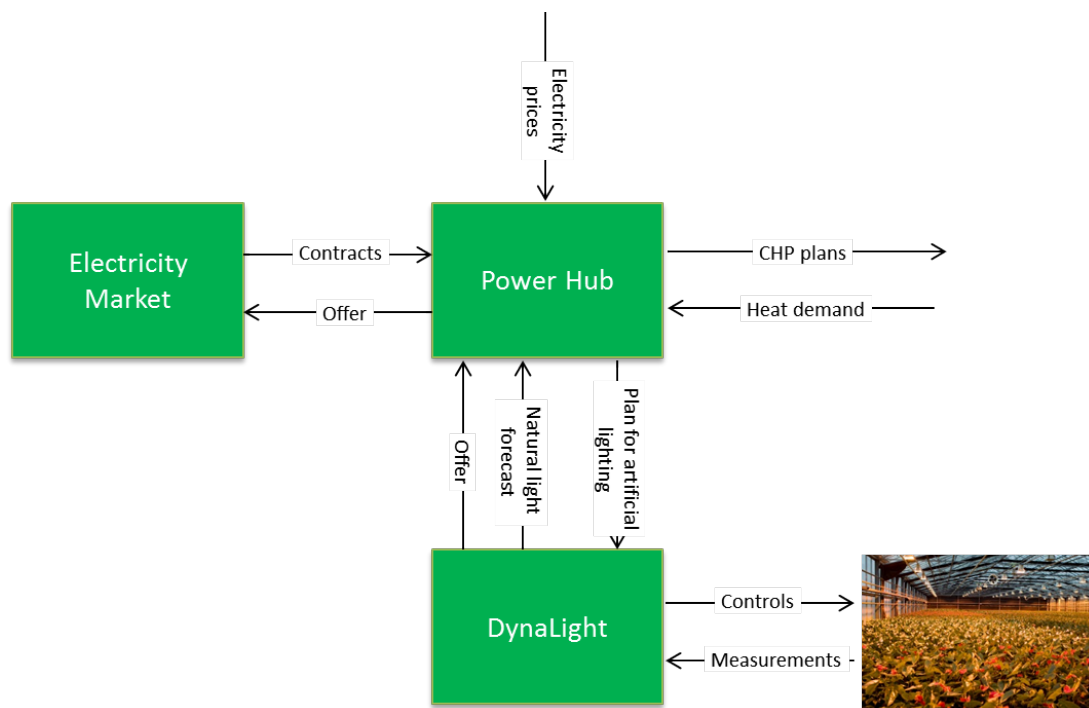
Figure 37. Architecture for integration between DynaLight NG and Power Hub

Power Hub conducts planning every hour around the clock based on the latest available information and send this to respectively the CHP plant, DynaLight NG, and if relevant also to the market for trading with electricity.

The study shows that it is possible to model the use of artificial lighting using the Power Hub terminology. However, it was decided not to pursue the integration of the greenhouse nursery's CHP with Power Hub further, as the historical data for CHP operation hours showed, that the CHP produces most of the electricity required for artificial lighting. Hence, only few hours will be available for electricity export during high price hours at the electricity spot market. These hours can easily be identified by DynaLight NG alone, as the multi-objective optimization process in DynaLight NG seeks to avoid electricity consumption in high price hours. Therefore, one may conclude that there is limited economically benefit from integrating and operating the CHP using Power Hub. A following up project aiming at a full integration of Power Hub and DynaLight NG at Knud Jepsen A/S was abandoned based on these reasons and the fact that Knud Jepsen A/S decided to change their primary source for heating to district heating during the project. This change had direct effect on the operation pattern of the CHP in such a way that it would be necessary to redesign all models of Knud Jepsen's CHP.

5.3   Characterization of LED fixtures and efficiency

A characterization of the LED fixtures and luminaires are important in order to be able to predict the light distribution and power consumption of a specific greenhouse lighting installation. One of the problems in choosing and comparing lighting products for greenhouse lighting is that for a majority of the products on the market there is no available photometric data or rather photosynthetic photon flux data. The necessary data are the total flux measured in a number of photons in the PAR region from 400-700 nm, and the corresponding efficiency and light distribution. The parameters and their symbols and measurement units are listed in Table 7.

Quantities	Abbr.	Symbol	Unit
Photosynthetic photon flux	PPF	Φ_{PPF}	µmol/s
Photosynthetic photon intensity distribution	PPID		µmol/(s sr)
Photosynthetic photon flux efficiency	PPF$_{eff}$	η_{PPF}	µmol/(s W)
Photosynthetic photon flux density	PPFD		µmol/(s m^2)

Table 7. Symbols and measurement units

The new state-of-the-art photometric facility at DTU Photonics has been used to characterize the luminaires and a procedure has been established to obtain desired photosynthetic photon parameters.

An integrating sphere spectroradiometer system, with a sphere diameter of 2m is used to measure the total spectral flux of luminaires. It can accommodate linear luminaires with lengths up to 1,5m and it has an external port of 0,6m diameter. The latter were used for the HPS luminaires. The integrating sphere measurement yields the total spectral flux $\Phi(\lambda)$ in the wavelength range from 360 nm to 830 nm. The total photosynthetic photon flux is calculated from

$$\Phi_{PPF} = \int_{400\,nm}^{700\,nm} \frac{\Phi(\lambda)\lambda}{Nhc} d\lambda, \tag{1}$$

where h is Planck's constant and c is the speed of light in the vacuum. The corresponding efficiency is calculated as

$$\eta_{PPF} = \frac{\Phi_{PPF}}{P}, \tag{2}$$

where P is the active power measured in Watt.
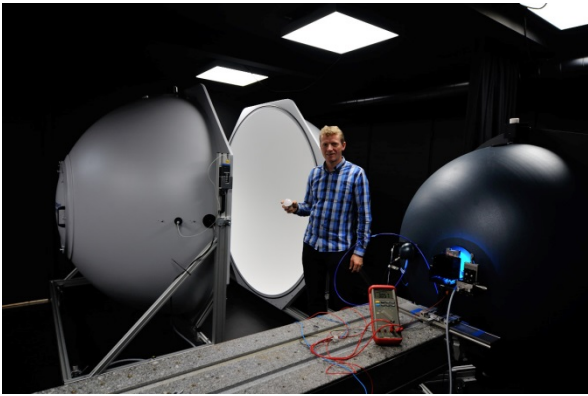
Figure 38. Top: 2m integrating sphere used to measure the total spectral flux of luminaires. Right: Goni-ophotometer used to measure the light intensity distribution of the luminaires.

The goniophotometer allows for the measurement of the light intensity as a function of emission angle. The facility accommodates luminaires with a largest dimension up to 2m and uses a camera to measure the far-field light intensity distribution. This is measured in candela pr. steradian and needs to be converted to photosynthetic photon intensity distribution. For this purpose the a scaling factor from luminous flux to photosynthetic photon flux is calculated from the measured total spectral flux $\Phi(\lambda)$:

$$K_{PPF-Lum} = \frac{\Phi_{\text{PPF}}}{683 \frac{lm}{W} \int \Phi(\lambda)V(\lambda)d\lambda}, \tag{3}$$

where $V(\lambda)$ is the the luminous efficiency function and the unit of $K_{PPF-lum}$ is lm/(µmol/s). This ratio, $K_{PPF-lum}$, holds for a specific spectral power distribution and is used to scale the measured light intensity distribution to a photosynthetic photon intensity distribution. The total spectral flux $\Phi(\lambda)$ is measured in the integrating sphere setup.

The luminaries were tested using the new international test standard CIE S 025/E:2015 "Test Method for LED Lamps, LED Luminaires, and LED Modules" and its preliminary versions as guidelines. Important aspects here are that the tests are conducted under an environment temperature of 25°C ±1°C, and very strict requirements on the power measurements. The most important issue on testing of LED based luminaires is the stability of the light output and power consumption. As seen in the graphs the total flux from a LED luminaire is high at turn on and decreases over time to a stable value, when the luminaires is thermally stabilized. This may take from 30 min. to 90 min. or more.

The assumption that the spectral power distribution is the same in all directions is valid for most luminaries but in cases where lenses are used to direct the light from the individual colored LEDs this is not the case. Two different examples are shown in the graph below where an LED luminaire shows very large variations in the spectral power distribution in different directions whereas the HPS luminaire has no significant variation in the spectral power distribution in different directions.

Figure 39. Measured spectral irradiance shown for different direction within the cone of light from an LED luminaire (a) and an HPS luminaire (b)

For the LED luminaire here it would be better to measure the SPD directly as a function of angle. This needs to be done in the far-field of the luminaire, e.g. at a distance of 10-15 times the largest dimension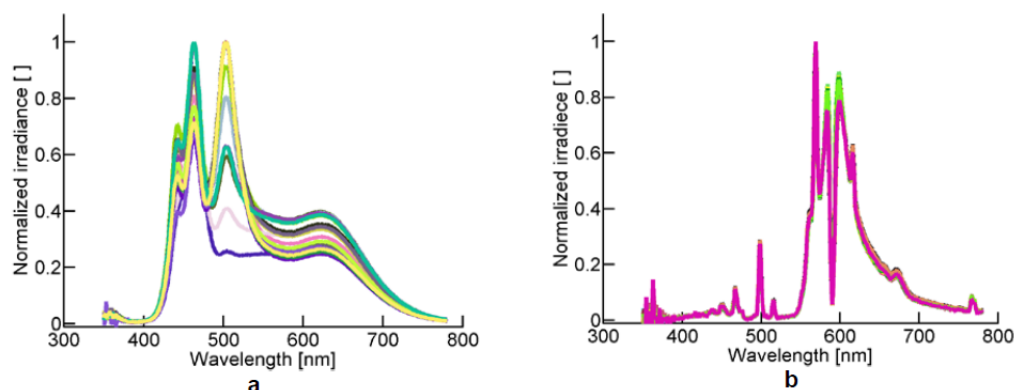 of the luminaire. A new far-field goniospectrometer has been installed in the photometric laboratory in order to overcome this problem and to be able to measure the spectral power distribution as a function of emission angle. This will allow for direct measurement of the PPID in the far-field and it is possible to compare the results of the two procedures.

In the project all the luminaires and fixtures that have been used in the experimental greenhouse setups have been characterized. The results are listed in the table below:

Lamp	Type	L3 ID	Luminous flux [lm]	PPF [µmol /s]	PPF/LUM ratio [µmol /s lm]	Power [W]	PPFeff [µmol /sW]
Fiona Lighting (Sunlight)	LED	L30481	25574	438	0.017	389.0	1.13
Valoya Bar 120	LED	L30482	3740	97	0.026	101.4	0.96
Fiona Lighting (BR)	LED RB	L30484	8670	783	0.090	382.0	2.00
HPS old	HPS	L30488	48698	637	0.013	624.0	1.00
HPS lights interaction	HPS	L30635	72506	956	0.013	646.0	1.48
HPS	HPS	L30636	70706	988	0.014	636.0	1.55
HPS growlight, Philips, 400W	HPS	L30624	44675	619	0.014	443.5	1.40
Fionia	LED RB	L30622	10711	957	0.089	503.7	1.90
Induktion	Induction	L30623	10599	308	0.029	420.1	0.73
Philips Growlight	LED RB	L30483	3340	254	0.076	127.0	2.00
Philips Growlight	LED RB	L30512	4520	459	0.102	192.0	2.40
HPS bulb	HPS	L30636	83099	1161	0.014	636.0	1.83
Philips Growlight (Blue)	LED B	L30889	1019	173	0.170	94.9	1.82
GPL toplighting mod. DR/B	LED RB	L30512	4786	451	0.094	187.1	2.41
GPL toplighting mod. DR/W	LED	L30915	8615	508	0.059	204.3	2.49
GPL toplighting mod. DR/B	LED RB	L30916	5436	502	0.092	193.9	2.59

Table 8. Measured total luminousl flux [lm], the photosynthetic photon flux [µmol/s], ratio between photosynthetic photon flux and luminous flux, power consuption [W], and photosynthetic photon flux efficiency [µmol/sW]for the different types of lamps and luminaires.

All the tested luminaires are designed for greenhouse top-lighting and include different types of LED luminaires and High Pressure Sodium (HPS) luminaires and one induction type lamp. It is observed from

the table that the HPS lamps and luminaires have photosynthetic photon flux efficiencies in the range from 1,0 - 1,6 µmol/sW while the measured efficiency for a HPS bulb is 1,8 µmol/sW. The Blue/deep red LED luminaires have efficiencies ranging from around 2,0 – 2,6 µmol/sW. It has been shown that the LED luminaires have a substantial higher PPF efficiency compared to the HPS luminaires. The results show that a reduction in energy consumption of approx. 60% can be achieved by changing old SON-T HPS luminaires with new LED luminaires, and a reduction of 32-40 % compared to newer electronic HPS luminaires. The measurements also show the increasing efficiency of 25-30% for the LED luminaires over the project period. The same type of luminaire from Philips have been tested in three variations where the first (November 2013) showed an efficiency of 2,0 µmol/sW and the last (january 2016) showed an efficiency of 2,6 µmol/sW. Hence, there has been a large increase in efficiency of the LED components and luminaires over the project period.

Three types of luminaires are chosen for this report to show the differences between a High Pressure Sodium (HPS) luminaire (L30635), an LED luminaire without optics (L30512) and an LED luminaire with optics (L30484) to direct and distribute the light evenly on a table. Both of these LED luminaires are based on blue and deep red LEDs.

The graphs below show the measured total spectral power distribution (SPD) for L30635, L30484, and L30512. Both LED luminaires are blue and deep red based having peaks at 450 nm and 660 nm. In the next graphs, these measured SPDs have been used in Eq. (1) to get the spectral photosynthetic photon flux distributions. These are shown in the PAR wavelength range 400-700 nm.
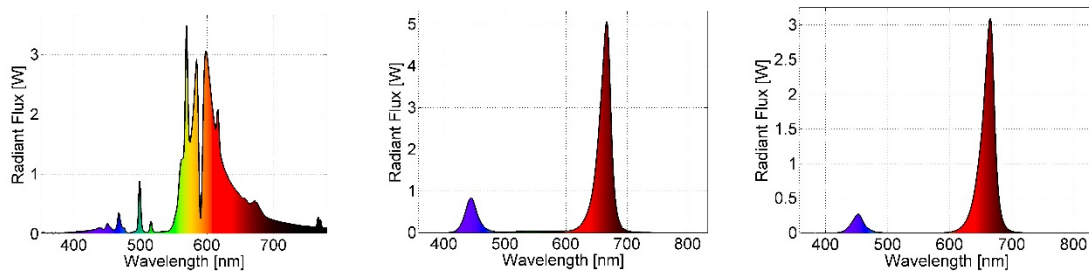
Figure 40. Measured total spectral power distribution for L30635, L30484, and L30512
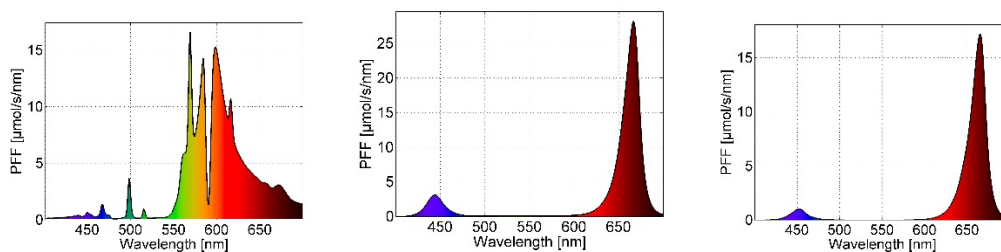
Figure 41. Calculated total spectral photosynthetic photon flux for L30635, L30484, and L30512 in the PAR wavelength range 400-700 nm.

The angular distribution of the photosynthetic photon intensity, [µmol/s sr], has been determined for all the luminaries based on goniophotometer and integrating sphere measurements. The results for the three luminaires are shown in the graph below:
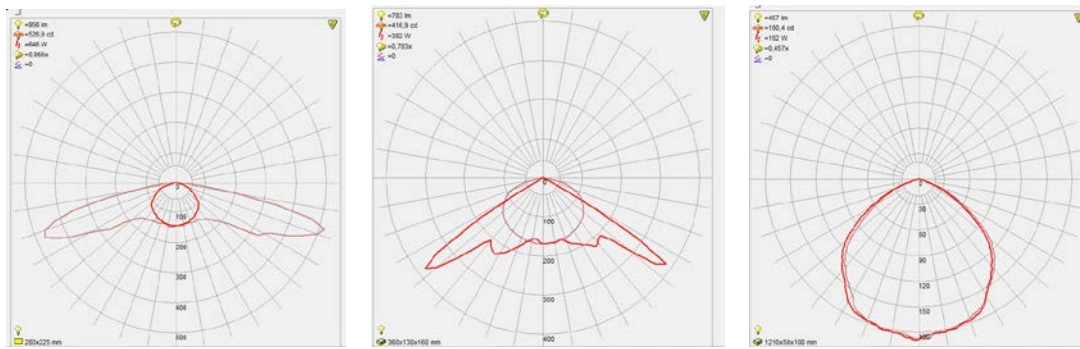
Figure 42. Measured light distribution shown in two perpendicular planes for L30635, L30484, and L30512.

The measured light distributions (LID) show the large differences in the three types of luminaires. The LED luminaires L30512 has no optics on the LEDs and produces a LID, which is Lambertian and the maximum intensity is downwards. The L30484 has cylindrical lenses on the individual LEDs to direct the light to the sides and the maximum intensity is seen at angles of approx. 55 degrees from the downward direction. This is almost like the LID from the HPS luminaire L30635, which has a reflector to produce an even more widespread light distribution in one plane, seen to be at 70 degrees from the downward direction.

The aim of the WP has been successfully achieved in provided a library of photosynthetic photometric data for a range of new top lighting LED and HPS luminaires, for both spectral power distribution, photosynthetic photon efficiency, and angular light distribution in terms of photosynthetic photon intensity. These can be used by the growers and horticultural scientist to design their lighting installations. These results have been distributed in ies-files that are the photometric standardized file format to be used in lighting simulation software like Relux and Dialux. These software packages are both freeware and we have used Relux to make lighting simulations for the greenhouse setups.

Simulation models of the greenhouse setups at KU have been established and used to calculate/simulate the photosynthetic photon flux density, µmol/s m2, at the plant level in a greenhouse setup, the corresponding task efficiency, i.e. the achievable photosynthetic photon flux density, PPFD per Watt of power, µmol/(sm^{2}W), looking at the number of luminaires and installed power needed to reach a certain mean value of PPFD in a specific greenhouse setup. Furthermore the spatial variations are instigated. KU has made onsite measurement of the PPFD in the greenhouse setup.

The graph below shows the 3D model made in Relux for the greenhouse setup at KU with 20 LED luminaires (L30512) installed.

Figure 43. 3D model for the greenhouse setup at KU with three tables and LED (L30512) installed.

The graph below shows the simulated photosynthetic photon flux density PPFD [µmol/s m^2] over the task area at 80 cm height in the KU experimental greenhouse facility.
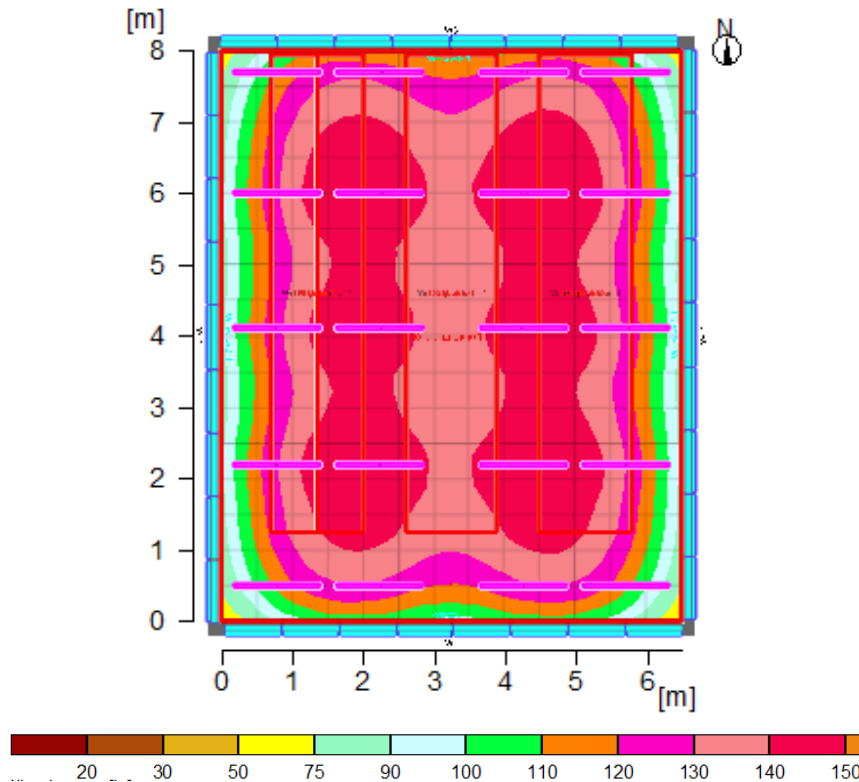
Figure 44. Simulated photosynthetic photon flux density [µmol/s m2] over the task area at 80 cm height in the KU greenhouse setup.

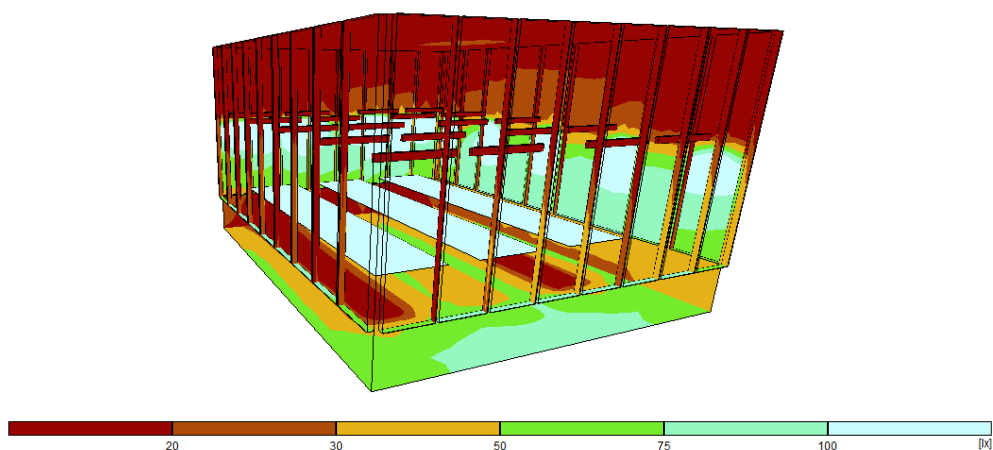The simulation shows a PPFD that varies from 70 to maximum of 150 µmol/s m^2. The mean value is 129 µmol/s m^2. The total photosynthetic photon flux from the lamps are 9140 µmol/s and the total power consumption is 3840 W. This yields a task efficiency, i.e. the achievable photosynthetic photon flux density, PPFD per Watt of power, of 73,9 µmol/(sm^{2}W) which would be 57.3 µmol/(sm^{2}W) at a mean PPFD value of 100 µmol/s m^2. Such 3D models with installed luminaires have been developed for the different setups in the project and provided to the growers to be able to work on themselves.

The project has resulted in an extensive comparison of greenhouse top lighting luminaires looking at both traditional old and new HPS luminaires and different types of LED based luminaires. Measurements have shown that the LED luminaires has photosynthetic photon flux efficiencies in the range 2,0 – 2,6 µmol/sW which is higher than the HPS luminaires and HPS bulbs which has been measured here to be up to 1,8 µmol/sW. Measurements over the project period of 3 years have shown that there has been a large increase in efficiency of the LED based luminaires and we may expect a further increase in efficiency in the coming years. It will be interesting to follow the development over the coming years to see when a saturation in efficiency will come and if it is possible to get higher total flux without increasing the size of the luminaires. Focus will also be on the cost of these luminaires which is still higher that for HPS luminaires. The lifetime is claimed to be long for LED based luminaires, but more research on accelerated lifetime testing is needed to see if these new types of luminaires actually keep a high flux maintenance over time when exposed to the greenhouse environment. The independent characterisation of the top lighting luminaires makes it possible compare the quality of different products, where many of these parameters are not readily available from the manufacturers. The total flux and light distribution that is provided for the different top lighting luminaires makes it possible to do simulations of the lighting installations. The standard photometric files either in ies og eulumdat file format have been provided in units of photosyn-

thetic photon flux and intensity making it possible to use lighting simulation software, like Dialux or Relux, to calculate the photosynthetic photon density in a greenhouse installation.

5.4 Characterization of plant species' responses to dynamic control of artificial lighting

On an everyday basis, the plants need a certain amount of daylight to achieve a certain amount of photosynthesis to sustain their growth. The photosynthesis has a nonlinear correlation with the proportion of light. The plants are only capable of absorbing up to a given amount of light, thus if there is enough natural light present then it will not be possible to accelerate the plant growth by using additional supplementary artificial lighting. Naturally, this has to be taken into account when planning the use of supplementary artificial lighting. In addition, other factors such as the CO2 content in the air and temperature also have to be taken into consideration, as these two climate parameters also affect the amount of photosynthesis that can be achieved under the given light conditions.

In order to evaluated the response of selected plant species to dynamic lighting, two series of greenhouse experiments were conducted using DynaLight NG in autumn 2014 and spring 2015. The experiments were conducted as four treatments performed in parallel in four identical greenhouse compartments. The first and second treatment were equipped with SON-T lamps, the first treatment had a fixed day length of 18 hours (control), whereas the light in the second treatment was run by the DynaLight NG software. The third and fourth treatments were equipped with LED lamps (Phillips). The third treatment was run in the same way as treatment two, whereas treatment four was run with a full implementation of DynaLight NG, meaning that both light, CO_2, and temperature were controlled by the DynaLight NG software. A number of different plant species and batches were grown in the four treatments over the two seasons (Table 9). The plants were harvested a maturation, meaning that plants from the different treatments were sometimes harvested at different time points.

Plant species	Cultivar	Received/sown	First harvest	Second harvest	Days between harvests	Veg/Gen
Tomato	Arvento RZ	18.09.14	08.10.14	28.10.14	16	Veg
		31.10.14	24.11.14	09.12.14	15	Veg
Rose	Alaska, Felicita, Apatche	16.09.14	30.09.14	21-27.10.14	21-27	Gen
	Alaska, Felicita, Apatche	21.10.14	03.11.14	26.11-09.12.14	23-36	Gen
	Alaska, Felicita, Apatche	20.01.15	03.02.15	02.03-08.03.15	27-32	Gen
	Alaska, Felicita, Apatche	05.03.15	20.03.15	13.04-23.04.15	26-34	Gen
Kalanchoe	Simone, Molly	19.09.14	17.10.14	21.11.14	24	Veg
	Jackie, Simone	17.10.14	14.11.14	19.12.14	30	Veg
	Jackie, Simone	17.10.14	14.11.14	19.11-09.12.14	5-25	Gen
	Evita, Simone	23.01.15	23.01.15	21.02-27.03.15	29-63	Veg/gen
Chili	Macho, Hot Fajita, Hot Burito, Snack Orange	10.02.15	03.03.15	17.03-06.05.15	13-63	Gen
Basil		-	26.02.15	16.03.15	18	Veg

Table 9. A summary of some of the plant species grown in the four treatments, harvest time points and whether they were grown as generative or vegetative

5.4.1 Energy use

The energy use was measured manually every day for all four treatments and calculated as a total value for the period 15.09.2014 - 19.12.2014 and the period 21.01.2015 - 05.05.2015. The cost of the energy used for light was calculated in relation to when the light was turned on and the price of electricity at the present time point. The data are presented in Table 10. The energy use for electricity (light) reflected the number of light hours and was higher in treatments with Son-T lamps. In contrast, the use of energy for heat was higher in the treatments with LED lamps. The day length was longer in all DynaLight NG treatments compared with the control treatment in autumn 2014, whereas the day length was shorter in the DynaLight NG treatments in spring compared to the control (Table 11). This affected the energy use in 2015, which was also lower in the DynaLight NG treatments compared with the control treatment. A

more realistic control treatment should have had a day length of 14 hours to be comparable with the DynaLight NG climates. In conclusion, the setpoints of the control treatment were too optimistic in 2014 and too conservative in 2015. Therefore, it was not possible to calculate an exact energy saving of the DynaLight NG treatments in these two experiments. However, it was still clearly shown that the use of LED light saved between 11-21% of the energy use in 2014, whereas all three DynaLight NG treatments were close to equal in costs in 2015. This probably reflected the short period of supplemental light used during the period.

Year	Treatments	Light hours	Light (KWh m^{-2})	% light of control	Light (€ m^{-2})	Top heat (KWh m^{-2})	Bench heat (KWh m^{-2})	Tot. heat (KWh m^{-2})	% heat of control	Tot. energy (MJ m^{-2})	% energy of control
2014 15.09 – 19.12	Control	1854	163	100	-	2	36	37	100	721	100
	DynaLight NG SonT	2077	182	111	362	2	30	32	86	770	106
	DynaLight NG LED	1973	100	61	325	74	17	91	246	689	95
	DynaLight NG (all) LED	1972	101	62	335	8	61	69	186	612	85
2015 21.01 – 05.05	Control	2022	138	100	-	24	121	145	100	1021	100
	DynaLight NG SonT	1684	46	33	79	12	120	133	92	643	63
	DynaLight NG LED	1718	25	18	68	25	127	152	105	637	62
	DynaLight NG (all) LED	1729	26	19	73	21	132	153	106	644	63

Table 10. Energy use in autumn 2014 and spring 2015 showing total number of light hours, electricity use for light in KWh, cost in Euro, energy use for heat and total energy use for both light and heat

5.4.2   Climate

The daily light integral (DLI) is presented for continuous measurements of light intensity taken above the plant canopies of Roses and Kalanchoe. The DLI reflected the day length in the treatments with supplemental light provided by SON-T lamps, whereas the DLI was lower in the treatments with LED lamps even though the day length was the same as in the DynaLight NG SON-T treatment (Table 11). This was not expected as similar effect (light intensity) should have been installed in the SON-T and LED treatments. The leaf temperature was lower in treatments with supplemental light provided by LED's in comparison to treatments where the light was provided by SON-T lamps, which was expected as the LED lamps do not emit infrared radiation. The effect was highest for the thick-leaved species Kalanchoe, which experienced a decrease in leaf temperature of 2-4 degrees. A detailed figure of the climate in spring 2015 is shown for the three DynaLight NG treatments, showing that only very small differences were seen between the treatment, and that supplemental light was not used in any of the treatments after the beginning of March (Figure 45).

Year	Treatment	Light hours (h day^{-1})	DLI roser (mol m^{-2} day^{-1})	DLI Kalanchoe (mol m^{-2} day^{-1})	LT roser (°C day^{-1})	LT Kal. (°C day^{-1})
2014 15.09-19.12	Control	18.4 ± 0.1	11.9 ± 0.2	10 ± 0.3	22.8 ± 0.1	23 ± 0.1
	Dynalight Son-T	20.8 ± 0.4	12.2 ± 0.3	12 ± 0.3	23.4 ± 0.1	24.5 ± 0.2
	Dynalight LED	20.4 ± 0.4	9 ± 0.3	10 ± 0.3	21.5 ± 0.1	21 ± 0.1
	DynaGrow LED	20.4 ± 0.4	8.6 ± 0.2	10.7 ± 0.3	21.2 ± 0.1	21 ± 0.1
2015 21.01-0505	Control	18 ± 0.1	13.2 ± 0.4	13 ± 0.5	19.8 ± 0.1	23 ± 0.3
	Dynalight Son-T	14.7 ± 0.3	9.7 ± 0.4	10 ± 0.5	21.7 ± 0.3	24 ± 0.2
	Dynalight LED	14.4 ± 0.3	8.6 ± 0.4	8 ± 0.4	21.2 ± 0.2	21 ± 0.2
	DynaGrow LED	14.5 ± 0.3	8.1 ± 0.4	8.4 ± 0.4	21.0 ± 0.2	21 ± 0.4

Table 11. Values for the number of light hours (day length), the daily light integral (DLI), and the leaf temperature (LT) in Roses and Kalanchoe in 2014 and 2015
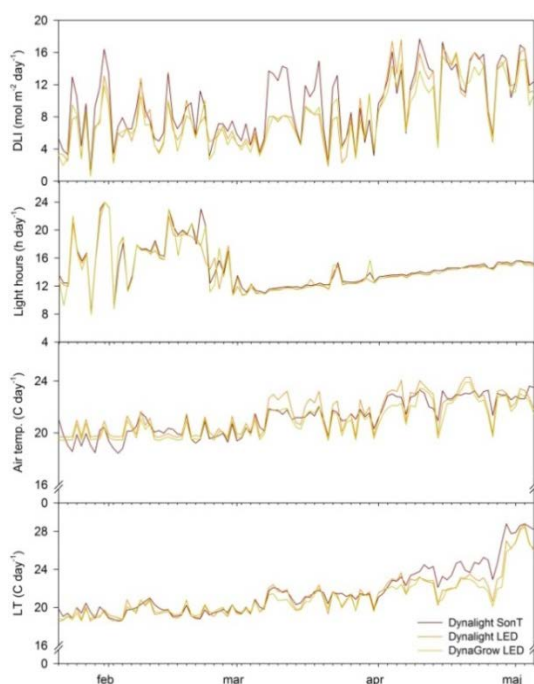
Figure 45. Climate in spring 2015

5.4.3   Plant growth

Plant growth is in the following reported for Roses, Kalanchoe and Chili. In general, the results are re-flecting that plant growth was related to the climate conditions of the treatments with species-specific and genotype-specific differences. All the plants grew well in the four climates and reached maturation at an acceptable time point.

5.4.3.1   Roses

For roses it was seen that there was no effect of treatment on the relative growth rate (RGR) and the number of flowers in roses in 2014, whereas the plants were growing faster in the control treatment in 2015 due to longer day length (Figure 46). There was a near-linear relation between RGR and the daily light integral (DLI) across all treatments, but no relation between DLI and the number of flowers, show-ing that more light results in faster growth, but have no effect on flowers in roses. Figure 47 show the relative dry weight measured as the dry weight increase between harvest 1 and harvest 2 of the two batches of the different rose cultivars (Table 9). The figure shows that the response of the different rose cultivars did not differ much between the three DynaLight NG treatments in 2015.
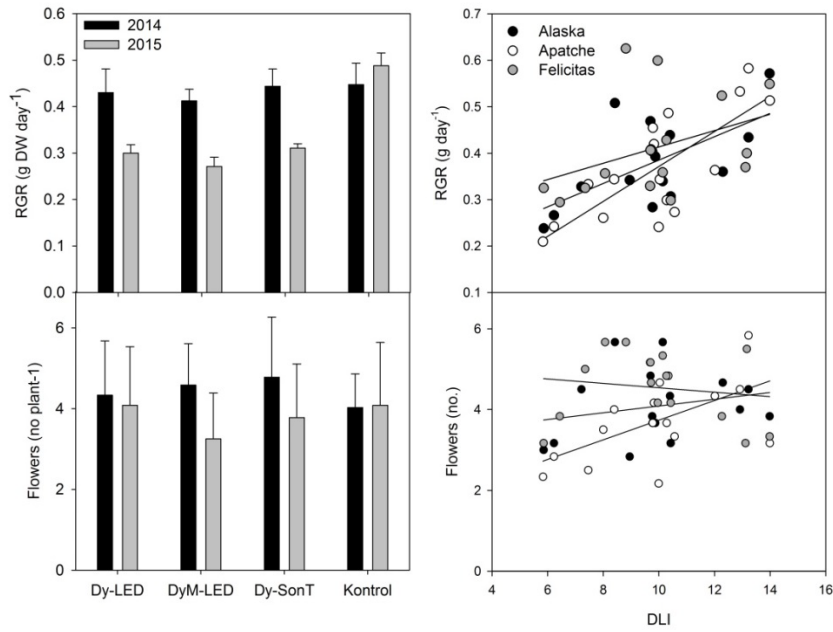
Figure 46. The relative growth rate (RGR) and the number of flowers shown for roses grown in four treatments and in relation to the daily light integral (DLI) measured in the treatments
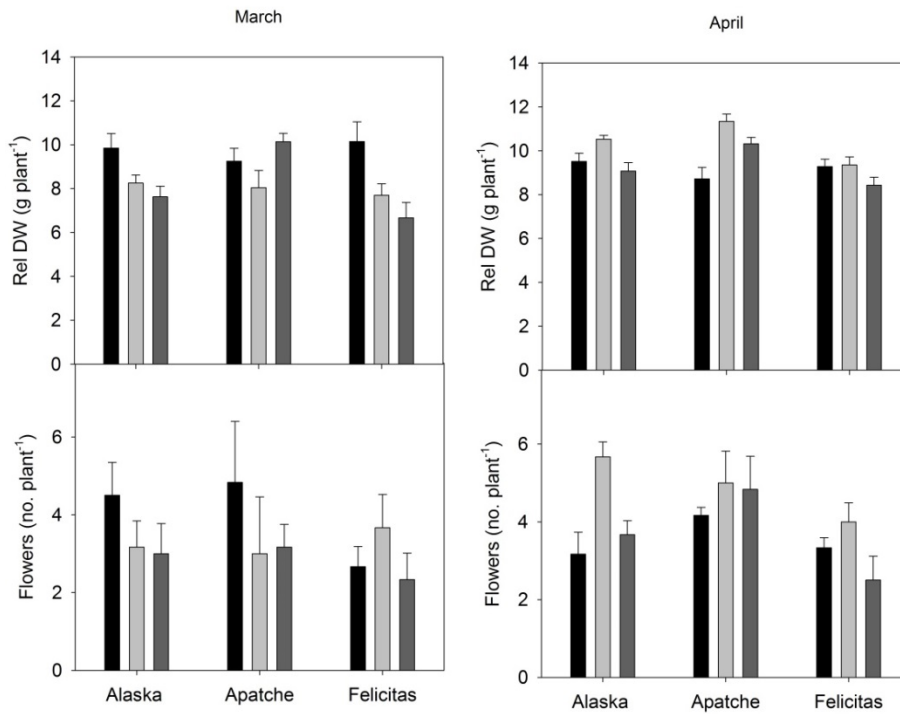
Figure 47. The relative dry weight and the number of flowers of the three different rose cultivars (Alaska, Apatche and Felicitas) harvested March and April (Spring 2015)

5.4.3.2 Kalanchoe

For the two Kalanchoe cultivars (Jackie and Simone) the dry matter production of vegetative plants was highest in the DynaLight NG SON-T treatment having the highest DLI in 2014 (Figure 48). In 2015 the control treatment had the highest DLI, but only one of the cultivars (Evita) accumulated more dry matter in this treatment, whereas Simone accumulated more dry matter in the DynaLight NG SON-T treatment (Figure 49). The same pattern was seen for the dry matter production of the generative plants depending

on the date of harvest, which differed between the treatments for plants harvested in 2014. The number of flowers also followed the same pattern, but the pattern was difficult to interpret due to the different harvest dates in 2014 (Figure 48). However, for the results from 2015 it was seen that less flowers were open at harvest when plants of both Evita and Simone were grown with LED as supplemental light source compared to SON-T (Figure 49). Differences in leaf temperature could possibly cause this effect.

Figure 48. Dry weight (DW), height, and number of open flowers in Kalanchoe cultivars grown in four treatments in 2014

Figure 49. Dry weight (DW), height, and number of open flowers in Kalanchoe cultivars grown in four treatments in 2014

5.4.3.3   Chili

Chili plants were only included in the 2015 experiment. Four cultivars were included but the treatments had no effect on the dry matter production of the four cultivars, which only differed between cultivars (Figure 50).
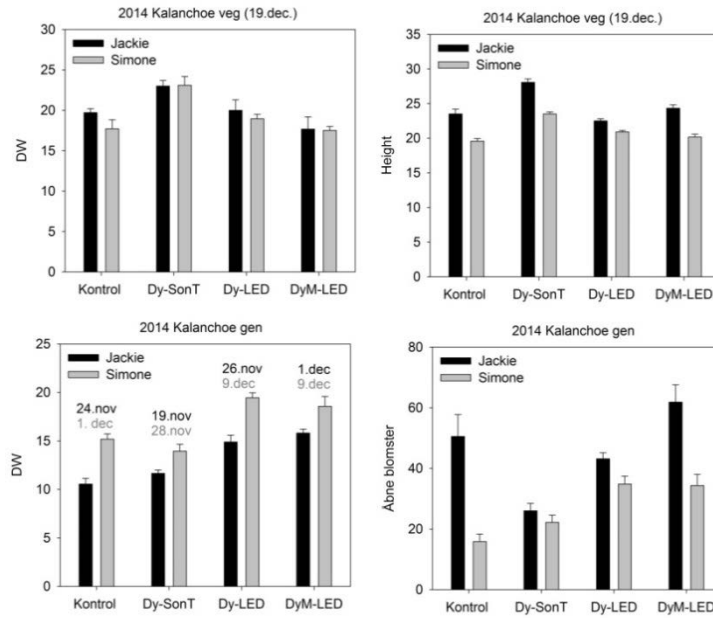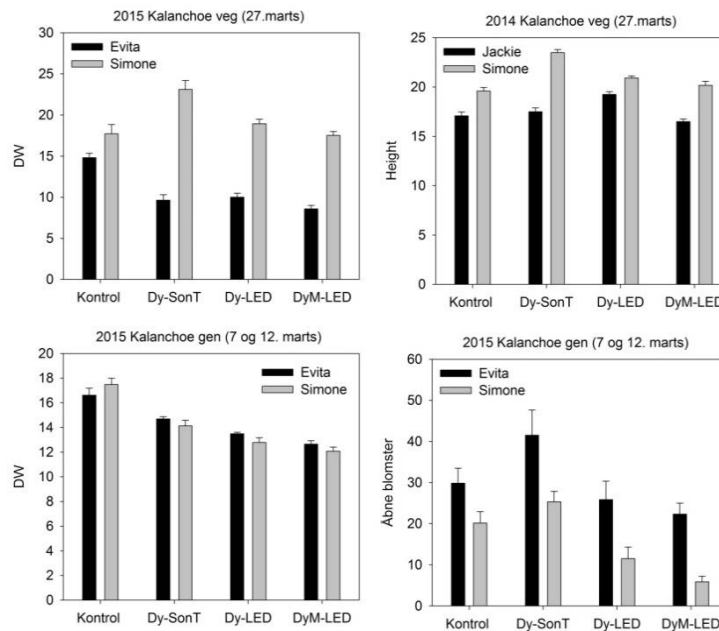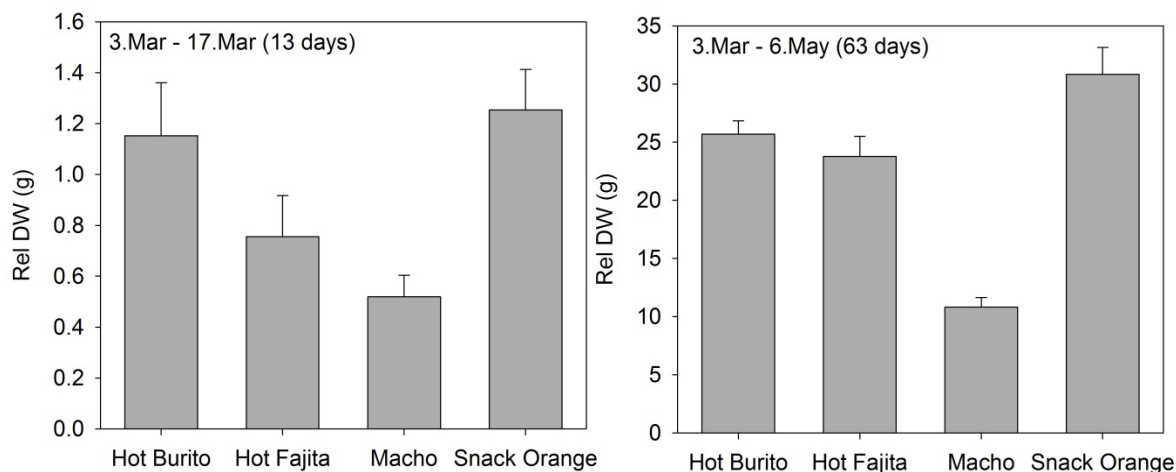

Figure 50.   The relative dry weight (DW) of four chili cultivars harvested in March and May

5.4.4   Conclusion

Overall, we could conclude that it was possible to produce a number of different plant species and cultivars in DynaLight NG treatments where the supplemental light sources are based on either SON-T or LED lamps, and where also the temperature and CO_2 are controlled by the DynaLight NG software. We could also conclude that savings are achieved in relation to a control treatment with a fixed day length, but only if the DLI is comparable between the treatments. The extra savings in energy by using LED light in comparison to SON-T light depends very much on how the heating is managed. There is an indication in Table 10 that suggests that top heating is a bad idea, whereas bottom heating is more feasible. Also the plant species could be affected differently showing that the leaf temperature of the Kalanchoe plants was much more affected by the light source than the leaf temperature of the Roses. Therefore, special attention must be given to control of the heating system when changing to LED lamps as the primary light source in greenhouse production.

The experiments have shown that the use of artificial lighting can be dynamically scheduled throughout the day without compromising the quality of the plants as long as the total photosynthesis goal is reached.

5.5   Test and demonstration of LED fixtures and dynamic lighting control

The new version of DynaLight NG has been implemented and tested in cooperation with the participating commercial greenhouse growers. Since the greenhouses use climate computers from different vendors, i.e., the Dutch company Priva and the Danish company Senmatic, it was necessary to extend DynaLight NG to support communication with both systems.

As part of implementation and test of dynamic lighting at the participating nurseries; Knud Jepsen A/S, Rosa Danica, Legro and Sogo Team, the project partner Lindpro has provided technical assistance and delivered hardware for installation of different combinations of SON-T and LED fixtures.

The commercial greenhouse grower Knud Jepsen A/S has implemented and tested DynaLight NG (Priva integration) in several of their greenhouse production areas. By using DynaLight NG for production areas with traditional SON-T lamp installations Knud Jepsen was able to save 25% of the light they would nor-

mally use with traditional lighting control, because DynaLight NG calculates the optimal schedule for giving the plants extra light. Furthermore, DynaLight NG enables a more accurate control of the production time by improve the timing of the production by reducing the light and temperature in periods with high level of natural light. Most of the production at Knud Jepsen is pre-sold and being able to deliver on a specific date is of key importance in order to fit with marketing. New control strategies has also been tested for a new 4000m2 large installation that combine blue LED lamps with 1000W electronic SON-T lamps, which are 30-35% more efficient than traditional SON-T. Tests show that 30 minutes of blue LED light in the morning may initiate the plants' photosynthetic systems, thereby preparing them to the higher level of light delivered by the electronic SON-T lamps. The blue LED lights are 90% more energy efficient than SON-T, and will therefore result in significant energy savings for the nursery. The savings related to using Blue LED lights are not restricted to electricity only, but reduce also the need for use of growth regulators, fungicides and insecticides. The use of blue LED light is found to results in higher compact plants, as well as the formation of more anthocyanins (colored defense compounds) in the plants. Finally, the results also show an improvement in product quality in terms of more color intensity of the flowers, which affects the sale price. By reducing the cost of electricity consumption and by reducing the cost and consumption of chemical growth regulation, and being able to deliver the products on time, Knud Jepsen stands strong in the international potted plant competition.

The commercial greenhouse grower Rosa Danica has implemented and tested DynaLight NG (Senmatic integration) in one of their experimental greenhouse areas. However, due to various version-related issues with a relatively old Senmatic installation, it has not been possible to carry out a full DynaLight NG installation for dynamic lighting control. Furthermore, Rosa Danica has chosen a fixed price agreement with their electricity retailer, so they are not able to get economically benefit from the combination of dynamic lighting control and variable electricity prices. Rosa Danica has in the project installed and conducted a series of experiments with new lighting fixtures: Fionia 600W LED fixtures 190W LED Philips Top-light, 600W electronic fixtures from Light Interaction and LED fixtures in combination with traditional 400W (50/50). During these experiments, a reduced plant growth was observed for the sole LED installations. The plant growth was reduced, because all experiments used the same settings for controlling the greenhouse climate, without taking the lack of heat emission from the LED fixtures into account. Based on this series of experiments, Rose Danica estimated that it is not economically viable for them to invest in LED due to the relative prices difference between the newer electronic SON-T and LED.

The commercial greenhouse grower Legro has performed experiments comparing three greenhouse compartments located in the same greenhouse and with the same climate control settings. Two compartments was equipped with old HGW lighting fixtures (174 pcs.) which all had been retrofitted with new light bulbs and the third compartment was equipped with a new combination consisting of two-thirds (82 pcs.) 1000W electronic SON-T lamps and one third (40 pcs.) new LED lamps. The experiment showed that the same plant weight could be achieved within the same production time with little marginal difference. The experiments also showed that salad grown in combined electronic and LED lights become more compact with more powerful leaves, in particular the variety 'Lolla Rosso' turned out to be more red, which is a highly desired effect. Measurements of the leaf temperature, showed a lower leaf temperature for combined electronic and LED light, which can be part of the explanation for the difference. Legro considers that the investment must be compared to the approximately 20 kW that they can save per. hour by shifting from traditional SON-T to a combination of electronic lamps and LED.

The commercial greenhouse grower SOGO Team has three times over the project period delivered plants to AU's experimental greenhouse facilities in Aarslev, in order to test how Phalaenopsis react to dynamic lighting control. In the same period, SOGO Team has conducted experiments with the following orchid species: Hunthleanthes, Oerstadella, Cambria, Oncidium, and Maxillaria at their own greenhouse facilities. During the project period, SOGO Team has been working with managing the artificial lighting in their greenhouses dynamically. Furthermore, they have been working on a new strategy for transporting plants by sea freight instead of aircraft. When plants are transported by sea freight, the plants have been

in total darkness for 4-5 weeks, and their exposure to light must thereby be progressively increased during the first three weeks.

6. Utilization of project results

The project results show that significant energy savings are achievable using dynamic lighting control and LED lamps, either in combination or separately. Using DynaLight NG with SON-T lamps allows the commercial greenhouse growers to save 25% compared to traditional lighting control and replacing SON-T lamps with LED lamps can reduce the energy consumption further by around 50%.

The project partner Knud Jepsen will continue to use DynaLight NG as currently installed, in order to uphold the energy savings achieved during the project. Together with SDU, Knud Jepsen will investigate the possibilities for co-optimization of dynamic lighting, CHP operation, and electricity trading on Nord Pool spot. AU will continue to use DynaLight NG for climate control experiments in their greenhouse test facilities in Aarslev. Finally, as a following up service, SDU will install an updated DynaLight NG version at the participating commercial greenhouse growers in the fall 2016.

As part of the project, DTU Department of Photonics Engineering has established new measurement procedures for the greenhouse top-lighting luminaires that will be used in the future work in DTU Photonics Quality laboratory as a measurement service. Furthermore, DTU has expanded their measurement facilities with a far-field goniospectrometer needed for accurate measurement of the angular distribution of photosynthetic photon intensity, [µmol/s sr]. DTU will provide the service of luminaire characterization in relation to greenhouse lighting, and will provide the photosynthetic photometric data and light distribution files needed for growers and horticultural scientist to design their lighting installations.

The project partner Lindpro will use the new insight on the effects of blue and white LED light when advising commercial growers on the purchasing of LED fixtures either for standalone lighting installations or in combination with existing SON-T installation. Similarly, Philips will use the new knowledge on selected plant species' physiological and growth-related responses to dynamic use of different types of artificial light in the design of future lighting fixtures.

The current status and action plan for commercialization of DynaLight NG is described in the following section.

6.1 Commercialization of DynaLight NG

During the project, it has been necessary to revise the business plan for DynaLight NG as Green Tech Solutions, which was originally intended as a distributor of the DynaLight NG software as part of a newly established company - DynaLight A/S, has withdrawn from the project. Likewise, DONG Energy decided during the project that they would not introduce their Power Hub concept on the Danish market. DONG Energy has instead chosen to focus on other European markets, such as England and Germany.

SDU has therefore developed a comprehensive business ecosystem analysis of the new opportunities the introduction of DynaLight NG creates for commercial greenhouse growers, as well as other players in the Danish electricity market. The analysis is described in the report DynaLight Next Generation - Business case analysis.

The report provides a systematic analysis of the new opportunities DynaLight NG gives players in the current electricity market and in the future Danish electricity market, as described in Energinet.dk report Market Model 2.0. The main results and conclusions from the report are as follows:

DynaLight NG will be able to bring value to four different market players in the Danish electricity market: The commercial greenhouse growers, balance responsible parties (BRPs), electricity suppliers, and aggregators.

The business plan's value propositions for each of the four actors are as follows:

1) Commercial greenhouse growers can reduce their electricity consumption without negative effects on plant quality or production time.

   DynaLight NG is sold directly to the commercial greenhouse growers, either as a purchase license, an annual license, or an annual fee depending on the yearly obtained energy saving.

2) DynaLight NG can help BRPs to reduce or completely avoid imbalance.

   DynaLight NG is sold to BRPs that through agreements with commercial greenhouse growers uses DynaLight NG and its OpenADR integration to up- or down-regulate artificial lighting in the greenhouses to achieve balance between announced energy consumption and production plans, and the actual consumption and production.

3) Electricity suppliers can attract more commercial greenhouse growers as customers and develop stronger relationships with them.

   DynaLight NG is distributed to electricity suppliers that will offer DynaLight NG as a service to their commercial greenhouse grower customers. Although electricity suppliers thereby will sell less electricity to each individual commercial greenhouse grower, the electricity supplier will gain a competitive advantage over other electricity suppliers. It is the most obvious choice that the electricity supplier enters into a service contract for delivering DynaLight NG to their customers, based either on an annual fee based on the number of commercial greenhouse growers end-users or the amount of electricity the electricity supplier delivers to its commercial greenhouse growers customers via DynaLight NG.

4) Aggregators can access and control energy flexibility in commercial greenhouse growers.

   By combination of the DONG Energy Power Hub concept and DynaLight NG aggregators can achieve control of the time of use and the quantity of electricity in commercial greenhouses. This will allow aggregators to act in the various electricity markets and optimize their profits. DynaLight NG can either be integrated with DONG Energy in a strategic partnership or licensed to DONG Energy.

The next step for bringing DynaLight NG to the market will be a dedicated market development project with the purpose of evaluating the proposed business value propositions. The project will be applied for as either an InnoBooster project at the Innovation Fund Denmark, or a market development project at the Market Development Fund.

7. Project conclusion and perspective

The project has developed the next generation of energy cost-efficient artificial lighting control that enables commercial greenhouse growers to adapt their use of artificial lighting dynamically to fluctuations in the price of electricity. The ability to do so is essential to secure the competiveness of the Danish commercial greenhouse sector, as fluctuations in electricity prices can be so large that it directly affects the production costs. Project results show that the newly developed dynamic lighting control software, DynaLight NG, allows greenhouse growers to adapt their use of artificial lighting to market variations in electricity prices without negative impacts on plant quality or production time. In fact, DynaLight NG provides commercial greenhouse growers with a more accurate control of the production time, than what was possible with traditional greenhouse climate computers. Experiments showed that the electricity savings that DynaLight NG can achieve depends on the installed lamp type. When used together with conventional SON-T lamps DynaLight NG can achieve an electricity savings of 25% compared to traditional artificial lighting control, and when shifting the lighting installation from SON-T to LED lamps it is possible to achieve a further electricity reduction of 50%. Besides cost savings from reducing the electricity con-

sumption, DynaLight NG also provides commercial greenhouse growers with cost savings from shifting the electricity use from high-price hours to low-price hours.

Presently the energy saving of shifting from SON-T to LED is the main argument used for future investments in new lighting installations. However, the project results also show that blue LED light has positive effects on leaf colors and the compactness of plants, as well as the formation of more anthocyanins (colored defense compounds) in the plants. It is therefore important to consider the right Blue:Red ratio when designing the next generation of LED fixtures. Today most lamps are designed with primarily 14-18% blue in red, which gives optimal growth of plants, which is not necessary the right ratio for all plant species in regards to morphological development (compactness) and content of pigments and secondary metabolites. LEDs have a great potential to improve the quality of plants during the first weeks of propagation, if it is moved from greenhouses to multiple layer systems in closed environment. The LED installation may need to give a higher light level than in the greenhouse, resulting in higher electricity use, but this will be strongly compensated by the decrease in the substantially higher cost for heating when moving the initial production with maximum pot density from one-glass layered greenhouses to insulated buildings. Because LEDs are relatively new on the market, the research on the detailed effect of spectral distribution of light is in its early beginning and considerably more research is needed to provide advice on which spectral distribution that can be used for what effect in which plant species.

The near future perspective is to continue the Development of DynaLight NG and the use of LED lighting in close collaboration with the Danish commercial greenhouse growers to improve their competiveness and secure high quality products.

8. Annex

Project publications and presentations

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