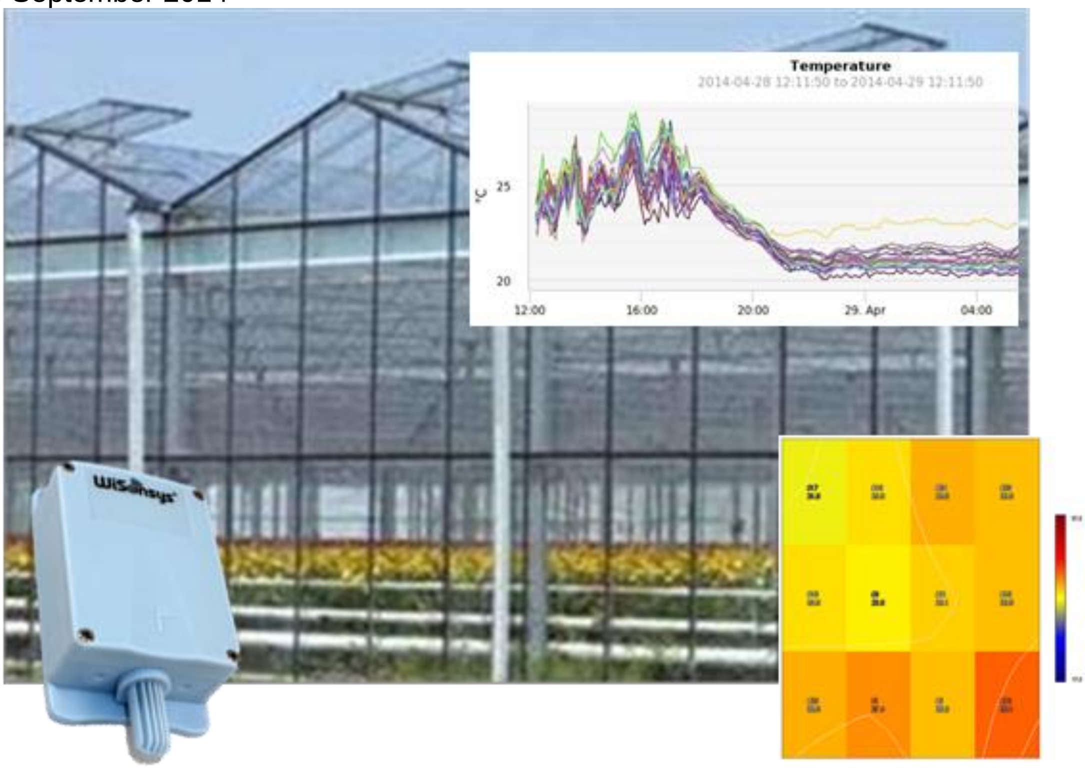
Final report master thesis

# Energy use and climate inhomogeneity in greenhouses

5 September 2014

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# Summary

In the horticultural sector in the Netherlands a large amount of natural gas is used to optimize the climate inside the greenhouse. The idea is that growers use higher temperature setpoints for their climate computer to compensate for the cold or wet spots inside the greenhouse. With higher climate homogeneity the temperature differences are smaller and there is no need for this compensation. So in theory the high setpoints could be lowered without having the risk of damage to the crop. The aim of this research was to estimate the energy impact of climate inhomogeneity in greenhouses and to investigate which factors could be responsible for climate inhomogeneity.
In literature the quantitative relation between a lower temperature setpoint is found in only one article, in which 1 K lower setpoint results in 10% less energy use. Also allowing higher relative humidity will result in less energy use. From literature study and by interviewing growers factors which cause inhomogeneity are found. There are static and dynamic cold spots. The static cold spots have infrastructural causes: faults in design, heating design, ventilation and screens. The dynamic places are caused by natural forces like outside temperature, solar irradiance and wind. From the measurements in the greenhouse could be concluded that during the day the inhomogeneity is in general higher than during the night. This is because during the night the greenhouse is better insulated, windows and screens are closed ,so there is less influence from outside. Measurements from two greenhouse are analysed. There are no significant and strong correlations found between factors and inhomogeneity. But the tendency is that the inhomogeneity is higher with extreme outside temperatures, hot or cold. Also the tendency is that inhomogeneity is higher with higher solar irradiance and with higher wind speeds.
It is still unclear what the energy saving potential is if the climate homogeneity is increased. Further research on this topic is needed. Growers will have to lower their heating temperatures and change vapour deficit settings to save energy. But growers will only do this when they are sure that the whole greenhouse stays within the allowed climate margins, so there is no negative effect on production.

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# 1 Introduction

## 1.1 Background

A greenhouse is a building consisting of glass or plastic panels in a metal frame used to grow plants. In a greenhouse the growing conditions are optimized. The most important conditions are temperature, humidity, light and $CO_2$ concentration. In figure 1.1 a schematic representation of a greenhouse is given. By trapping the solar radiation the inside of the greenhouse will heat up. In the Netherlands with relatively cold and wet climate additional heating is required to optimize the greenhouse climate.

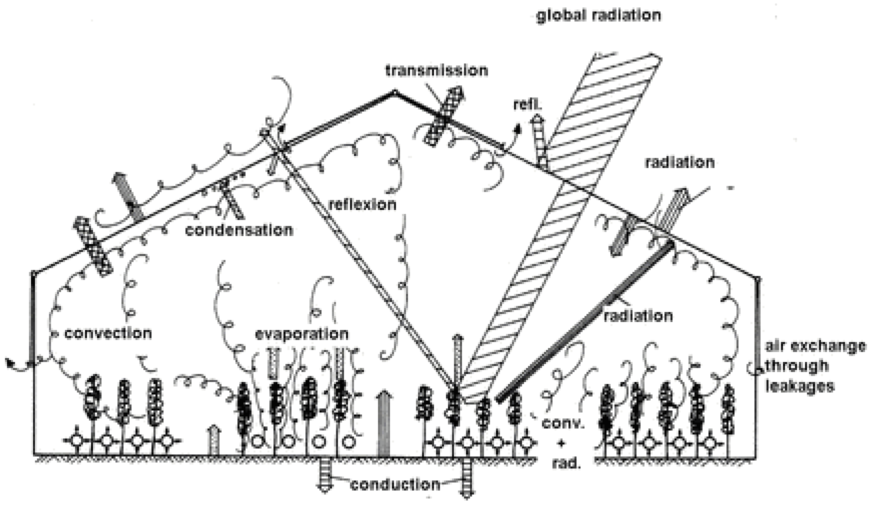


**Figure 1.1: A schematic representation of the radiation and energy balance of a greenhouse (Berkem, 2009)**

The greenhouse horticultural sector in the Netherlands used about 127 PJ of natural gas in the year 2012 (CBS Statline, 2014). This is more than nine percent of the total natural gas use in the Netherlands.

In the horticultural sector energy efficiency has high priority, because the energy costs are high for the greenhouse owners. The energy costs contribute about 25 percent to the total costs of the greenhouse (BINternet, 2014). In the last two decades the energy use per square meter greenhouse area decreased with 33% to around 27 $m^3$ natural gas. Despite the less energy use per square meter, growers reached a 39% higher production per square meter, which is a remarkable improvement in energy efficiency (van der Velden & Smit, 2013). With probably increasing natural gas prices in the future and sustainability issues, the need for energy efficiency improvements and costs reduction in greenhouses is still present.

## 1.2 Problem definition

In the last decades the greenhouse size has increased, a typical modern greenhouse has a size of 4 ha (200 x 200 m). In greenhouses there is often an inhomogeneous climate, there are horizontal and vertical temperature and humidity differences. This will lead to inequalities in plant growth and thus results in lower crop production. There is also a higher risk of diseases, like fungal diseases (Wientjens, 2013; Knoll & de Jong, 2010). To compensate the lower temperatures and high humidity in some parts of the greenhouse, the assumption is that growers use higher setpoints for temperature, which requires extra heating. Extra heating causes extra evaporation, this will result in higher humidity. To compensate for the higher humidity ventilation is used, but ventilation in most cases means heat losses. This again will

result in extra heating. These relations show that inhomogeneity of the greenhouse climate results in extra energy use and thus extra costs for the growers.
Vertical climate differences are not the most important to measure, because they also occur in nature and do not affect the crop which is often in only a small horizontal layer (Os et al., 2006). The growers want a uniform crop, which could be harvested at the same time. Horizontal climate differences results often in unequal growth and makes the harvesting more difficult.
The greenhouse climate is controlled by a climate computer system. The computer controls the appliances present in the greenhouse. The computer settings and outputs are the result of measurements done by in most cases only with a few sensors per hectare. In most greenhouses the inhomogeneity is not quantified and therefore insight in the homogeneity is needed. Wireless sensors could be used to measure climate differences in greenhouses. Those sensors can simultaneously measure climate conditions at different locations in the greenhouse (Van Tuijl et al, 2008). Different researches with the use of these sensors has shown that quite large temperature and humidity differences could occur in greenhouses, up to 6 K (Wientjens, 2013; Knoll & de Jong, 2010; Balendonck et al., 2010).

There are technologies on the market and developed which try to improve the greenhouse climate and/or save energy. Examples of those technologies are multiple screens, air handling units, air hoses, vertical fans, air circulation systems, low temperature heating or dehumidification.
There is little knowledge of the effect on climate inhomogeneity of those technologies. Also with the increasing number of different installations in a greenhouse the effect is difficult to estimate. Some of these techniques are relatively new and needs to prove itself in practice.
Also combinations of those techniques will make the effect on climate more difficult to estimate. So there is still a lack of knowledge how to apply these techniques in a useful manner and their effect on energy use.
The idea is that growers use higher temperature setpoints for their climate computer to compensate for the cold or wet spots in the greenhouse. With lower inhomogeneity the temperature differences are smaller and there is no need for this compensation. So the high setpoints could be lowered without having the risk of damage to the crop.

## 1.3 Aim

The aim of this research is to estimate the energy impact of climate inhomogeneity in greenhouses and to investigate which factors could be responsible climate inhomogeneity.

## 1.4 Research questions

The main research question is: What is the energy saving potential for increasing the climate homogeneity in greenhouses?

To answer this question the following sub questions were used:

1. *What is the quantitative relation between inhomogeneity and energy use?*
2. *What factors are causing climate inhomogeneity?*
3. *What is the measured climate inhomogeneity in the greenhouses?*
4. *What kind of relations between the factors (from 2) and the inhomogeneity (from 3) could be found?*

# 2 Methodology

In this chapter will be described how this research is done and what methodologies are used. Also the most important definitions and concepts are given.

## 2.1 Literature study

The first part of the research was a literature study. To answer sub questions 1 and 2 information from earlier studies was needed. Sources that were used are: publications from the ISHS (International Society for Horticultural Science), publications of the greenhouse division of the Wageningen UR (University & Research centre), reports of research done by TNO and other scientific articles and research reports of other institutes.
The keywords that were used are: homogeneity, uniformity, greenhouse, climate, temperature, wireless sensors, horticultural.
The literature study was the basis for the remaining part of the research. It gave a good indication on which factors should be focused in the data collection and analysis part.

## 2.2 Interviews

Interviews with growers and experts were used to answer sub question 1 and 2. The growers and experts that are consulted are the ones which participated in one of the projects of TNO or with growers who already did measurements with wireless sensors. The growers which are consulted are the ones which already have some experience with inhomogeneity measurements. In Appendix II the list of interview questions is given, the questions are in Dutch.

## 2.3 Data collection

A large part of the research was the collection of data. The temperature and humidity distribution was measured in a greenhouse with wireless sensors, to answer sub question 3.

### *2.3.1 Climate computer data*

Every greenhouse has its own climate computer. This computer controls the heating system, amount of ventilation by the window openings and screen positions. The settings are calculated on basis of data measured with measurement boxes inside the greenhouse and meteorological measurements outside the greenhouse. This data will contain information of the heating, ventilation and weather conditions. Data from this computer was retrieved for the same period as the measurements with the wireless sensors.

### *2.3.2 Wireless sensors*

For the measurements 25 wireless sensors from Agrisensys are used. These sensors are able to measure temperature and relative humidity. In figure 2.1 an overview of the wireless sensor network (WSN) is given. The inaccuracy of the sensors is ±0,3°C at 25°C. For humidity the inaccuracy is 1,8% at relative humidity ranging from 10% till 90%. Above 90% the inaccuracy could be up to 4%. The data from the sensors is transmitted at a 5 minute interval to a server via the base station. If the base station is out of reach for the sensor the signal goes to the range extender. On the server there is software which processes the data into graphs and maps. Temperature and humidity difference are directly visible (Wientjens, 2013). The original data or average data on different time intervals was downloaded for further analysis.

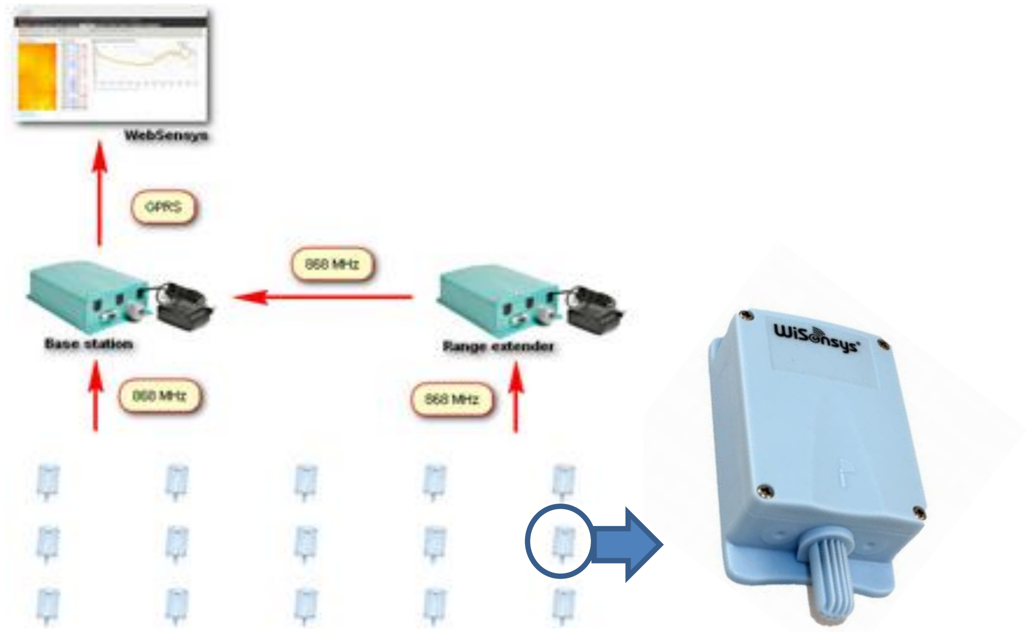


**Figure 2.1: Overview of the wireless sensor network (Agrisensys, 2014)**

For every measurement in a greenhouse a matrix of sensors was mapped. After the installation of the sensors in the greenhouse the location of the sensors was put into the software. This made it possible for the software to show temperature and humidity maps. How the matrix of sensors is distributed in a greenhouse depends on the properties of the greenhouse. In most cases there was measured in a horizontal plane. To get a good insight of the temperature distribution insight the greenhouse the sensors were distributed at the same horizontal level throughout the whole greenhouse. The optimal matrix size depends on the dimensions of the greenhouse. The location of each sensor number was precisely mapped.

#### *2.3.3 Data from previous measurements*

TNO had datasets available from previous studies on climate inhomogeneity. These data sets contain data from the wireless sensors and the climate computer. One of these datasets data was also used for analysis.

### 2.4 Analysis

The analyses of the data from the wireless sensors and from the climate computer were used to answer sub question 4. From the sensor data the temperature inhomogeneity was calculated. Because humidity and temperature are more or less the opposite of each other only the temperature data was used. Also from the website from Agrisensys the temperature and humidity distribution maps were consulted. The relations between homogeneity and the influencing factors were investigated by combining the sensor data and data from the climate computer. With the use of Microsoft Excel correlation maps were created to look for correlations between the factors and the inhomogeneity. But also to see correlations between the factors. Next to this, graphs with scatterplots and spider diagrams were created to visualize the relations.

## 2.5 Definitions

Here some definitions are given:

**Homogeneity**: Homogeneity is a measure for how uniform something is. In this research the focus is on the temperature homogeneity inside a greenhouse. There are always small differences in temperature, but to what extend temperature differences are acceptable is not strict. The Dutch environmental certifying organisation aims to stay within a range of maximum 1,5 °C horizontal temperature difference (SMK, 2014). Agrisensys uses more or less the same range with a range of ± 0,75 °C from the average to make cold and hot maps with percentages of how much of the time a sensor is within this range (Agrisensys, 2014). So homogeneity could be quantified with a percentage of the number of sensors within the temperature range or with absolute temperature differences ($\Delta T = T_{max} - T_{min}$). For the absolute temperature difference all sensors within the same horizontal level are used. In this research the absolute temperature difference is use, because this method is used the most.

**Temperature (T)**: Temperature is a measure for hot and cold. In this research degrees Celsius will be used as unit.

**Relative Humidity (RH)**: The relative humidity is the ratio of the partial pressure of water vapour in the air to the saturated vapour pressure of water at a given temperature. It is expressed as a percentage.

**Vapour deficit**: Vapour deficit is the difference between the actual amount of water in the air and the maximum amount of water vapour the air can hold when it is saturated at a certain temperature. The unit is g/m$^3$.

**Sensor**: A sensor is a small device which measures a physical quantity, in this research a sensor which measured T and RH was used. The sensor converts it into a signal which is send through the air to the receiver.

**Wireless Sensor Network (WSN)**: A WSN is a network of spatially distributed autonomous sensors to monitor physical or environmental conditions.

**Setpoint**: A setpoint is the desired process output of automatic control system. In this research the climate setpoints (for T or RH) of the greenhouse computers are relevant.

# 3 Results literature study

In this chapter the results of the literature study are given. First an overview is given of the literature about inhomogeneity and energy use. Next the use of Wireless Sensor Networks (WSN) in greenhouses will be described. This is followed with a summary of studies in which WSN are used to investigate causes and solutions for climate inhomogeneity. Also models could be used to investigate climate inhomogeneity which is discussed in the last part of this chapter.

## 3.1 Relation climate inhomogeneity and energy use

Esmeijer & Nijs (2000) gave an example for a tomato greenhouse of 2 ha in which a one degree higher temperature setpoint results in 10% more energy use (Esmeijer & Nijs, 2000). This is the only research in which a relation between a higher temperature setpoint and energy use is given. A higher temperature setpoint is used to compensate for cold and wet places in the greenhouse. Other researchers refer often to Esmeijer & Nijs and use it as a rule of thumb, but it is not clear how they calculate this 10% extra energy use. This also shows that extra research on this subject is needed.
In many greenhouses the relative humidity (or vapour deficit) is also used as a setpoint. De Zwart (2014) researched the effect of the maximal allowed relative humidity in a tomato greenhouse. With maximum RV of 84% the heating requirement is about 17 $m^3/m^2$ natural gas per year. With a maximum RV of 93% the heating requirement is reduced to about 10 $m^3/m^2$ natural gas per year. This is a reduction of more than 40% (Zwart, 2014).
Both researches do not show to what extend the temperature and humidity setpoint could be changed and whether growers really use higher setpoints because of inhomogeneity.

## 3.2 Use of Wireless Sensor Networks

Os et al. (2006) investigated the need by growers for a wireless sensor network, which could be consulted online. Growers wanted a WSN to gain insight in climate inhomogeneity. But they also want to use the sensor measurements to regulate the climate (Os et al., 2006). The use of the sensor measurements for climate regulation is still not possible. Because this requires new software systems for climate computers and the measurements of the sensors are strongly influenced by solar irradiance.

In 2008 Os et al. investigated the use of wireless sensors in practice. They found on basis of hourly averages a maximum of 9 K, minimum 1,5 K and on average 3.8 K inhomogeneity. They conclude that the interpretation of WSN data is difficult and uncertain. Uniform preconditions are needed to perform measurements. These preconditions should include: when to measure, how many sensors, height, duration, etc.(Os et al., 2008).

The results of the literature review of Van Tuijl et al. (2008) showed that WSN in the horticulture sector is not used often till 2008. Many papers describe the theoretical scientific advancements of WSN, but practical introduction of WSN in horticulture needs the input of experiments. One experiment showed that a WSN can be used to measure the T and RH at 100 points within a large greenhouse (Van Tuijl et al., 2008).

## 3.3 Causes for inhomogeneity

Balendonck et al. (2010) distinguishes two types of climate differences: static cold and wet places and dynamic cold and wet places.
The static places have infrastructural causes. Examples are greenhouse design, heating design, ventilation and screens. The location of these cold places does not change over time.

Once these places are discovered they could be fixed by changing the infrastructure (Balendonck et al., 2010). In good designed and well maintained greenhouses the number of static cold places should be low.
The dynamic places are caused by natural forces. Which are for example: Inside climate, solar radiation, wind and outside temperature. These places do not always have the same location. So growers have to deal with this, that is why they use larger margins for the climate computer to prevent damage to the crop (Balendonck et al., 2010).

Knoll & De Jong (2010) looked at vertical climate differences in a greenhouse with tomato plants. The top part of the tomato plant is has on average a two degrees higher temperature and 10 percent lower humidity, due to solar radiation. They also found horizontal differences. With increasing temperature differences between inside and outside and increasing ventilation by the air hoses the inhomogeneity increases. Thermal currents due to the gradient of the greenhouse roof cause lower temperatures at the facade (Knoll & de Jong, 2010).

Wientjens (2013) also found that WSN gives good insight in the horizontal temperature differences. From analysis is found that slightly opening the screens is a major cause of climate inhomogeneity. Wind velocity and outside temperature are the main external drivers during the night. During the day the solar radiation is of influence (Wientjens, 2013).

Balendonck et al. (nd) monitored the spatial distribution of T and RH with 100 sensors. They observed long-term averaged spatial differences for temperature of 1,0 till 3,4 C and the actual spatial differences are larger. In the greenhouse they measured, nine sensors per hectare (33 m apart) were necessary to detect long term cold or wet spots (Balendonck et al., nd).

Campen & De Gelder (2007) state that there will be always hot and cold spots inside a greenhouse. This is caused by physical transport processes and the placing of the heating. Heating is located in lower levels inside the greenhouse. The hot air will rise and find in most cases a cold glass roof, so this will result in air circulation. The horizontal temperature differences are about 20 - 25 percent of the temperature differences between the inside and the outside of the greenhouse. By reducing the vertical temperature differences also the horizontal temperature differences will be reduced. This could be done with the use of an energy screen.
Next to this they also found technical shortcomings which could cause climate differences. Examples are: broken or not fully closing windows, no controllable heating and the use of the screens (Campen & De Gelder, 2007).

In the research of Carrara et al. (2008) the greenhouse climate is measured in three different vertical environments. Environment 1 (0-20 cm above the bench, thus in plant layer, environment 2 (20-80 cm) and environment 3 (0.8-1.4 m). Results show the larger the distance to the bench the higher the temperature (and the lower the RH). Environment 1 showed remarkable differences with environment 3 where traditional monitoring systems are usually located (Carrara et al, 2008).

Sapounas et al. (2008) used geostatics to create spatial prediction maps for temperature. They used measurements at 25 locations in small 8*15m greenhouse with tomato crop. They found temperature differences in both horizontal and vertical planes. This approach is useful to comprehend the random variation of parameters related to the crop canopy (Sapounas et al., 2008)

Suay et al. (2008) monitored the temperature and humidity in a vertical plane. Mapping the data could be used to compare the results with models. Models are done with the use of CFD

(Computational Fluid Dynamics). But how to interpolate the data needs further study. They observed larger variations in minimum and maximum temperature during day times (Suay et al., 2008).

Bontsema et al. (2012) investigated an air hose system through which a mixture of heated outside air and recirculated greenhouse air is blown under the crop (roses). The idea of this system was that it should lead to smaller temperature differences in the greenhouse and to a cheaper removal of moisture from the greenhouse compared to a so-called minimum pipe. Measurements showed that the horizontal temperature differences (6-8 degrees) were mainly caused by a cold air flow above the screen with could not be compensated by the air inlet system. This problem has been solved by installing vertical partitions in the ridge (nokschotten) above the screen. The optimization of the air hose system and the vertical partitions reduced the temperature differences to 2 degrees (Bontsema et al., 2012).

In the research of Gieling et al. (2010) temperature effect measurements of air handling units(AHU) were performed in semi closed greenhouses. In these greenhouses AHU are used for cooling. The effects of temperature uniformity in vertical and horizontal planes are investigated. They conclude that cooling above the crop results in a better vertical climate. Cooling from underneath the crop could cause horizontal temperature differences.

Knoll (2014) gave a summary of the most important factors causing climate inhomogeneity both horizontal and vertical, based on literature and own research.

- The first one is uneven conversion of solar radiation into heat across the greenhouse. Some places in the greenhouse will receive more radiation than others and with different types or sizes of plants the conversion to heat will be different.
- Another one is ventilation. Ventilation by the windows in combination with wind could result in an air flow inside the greenhouse.
- Cold outside air is entering the greenhouse on one side and the relatively hot air is leaving at the other side of the greenhouse.
- Sometimes there is a weak vertical distribution of the ventilation air. The ventilation air with low humidity, entering through the roof windows, will not mix well with air in humid places in lower levels of the greenhouse.
- With the use of screens in greenhouses another problem became clear. The cold air above the screen is heavier than warm air. Therefore the cold air will flow to the lowest points above the screen. If this air has the possibility, it will fall down on the plants trough openings in the screen. This results in lower temperatures at plant level where the screen is open.
- Defects in the greenhouse construction or the climate control system could also result in inhomogeneity.

### 3.4 Model experiments with CFD

The models with CFD (Computational Fluid Dynamics) are mainly focused on the relation between ventilation and temperature.

Sase (2006) showed in a review article that the internal air movement in a naturally-ventilated greenhouse is affected by many factors. Examples are wind velocity, wind direction, internal and external temperature differences, greenhouse structure and vent configuration (shape, size). For different types of greenhouses the results of studies are summarized. The studies are done with the use of scale models, field experiments and CFD techniques (Sase, 2006).

Karcira et al. (2008) looked at the effect of vent configurations and wind speeds on temperature distributions with the use of 1:16 greenhouse models. The use of side vents in combination with roof vents showed increased temperature uniformity compared to other cases (Karcira et al., 2008).

Bournet and Ould Khaoua (2008) found that for their study cases (with CFD modelling) the best compromise between ventilation and homogenization of climatic parameters at the plant level is found by combining a windward roof vent for the windward span and symmetric (both windward and leeward) roof vents for the rest of the greenhouse (Bournet & Ould Khaoua, 2008).

### 3.5 Conclusions literature study

From the literature study the following became clear:
- The relation between energy use and inhomogeneity is not investigated frequently. Only one paper gives an energy saving potential of 10% for a 1 K lower temperature setpoint. Another research gives an energy saving by increasing the maximum allowed relative humidity.
- WSN are good applicable to measure climate inhomogeneity, but uniform preconditions and more use in practice is needed.
- Research with WSN has shown that there are static cold and wet places and dynamic cold and wet places. The static places are caused by infrastructural causes and the dynamic places are caused by natural forces.
- Infrastructural causes for inhomogeneity could be faults in design, heating design, ventilation screens and other appliances such as AHU’s.
- The natural forces which cause climate inhomogeneity are: outside temperature, solar irradiance and wind.
- Sometimes models are used to calculate the effect of influencing factors on the temperature distribution in the greenhouse. These models are mainly focused on ventilation and wind.

# 4 Results interviews

In Appendix I the interview questions which are answered by the growers are given. Growers, who performed temperature measurements to investigate climate inhomogeneity, were interviewed. A total of eight growers were visited for an interview. In Appendix II an overview of the answers given by the growers is given. This chapter will summarize the answers given by the growers, in the same subdivision as in the interview: period before measurements, during the measurements and after the measurements. There will be started with a short description of the properties of the greenhouses.

## 4.1 Properties of greenhouses

Of the eight growers, four are growing vegetables; three are growing tomato and one paprika. The other four are growing flowers or potted plants; two are growing gerbera and two orchids. The size of the greenhouses is in general between 2 and 3 hectares, sometimes growers have multiple greenhouses. Two of the greenhouses are larger, of about 5 hectares. The height of the gutter is in most of the greenhouse about 5 till 6 m, only one of them has a gutter height of 3 meters. The year of construction of the greenhouses is in the range between 2003 till 2013 and one old greenhouse build in 1990.

## 4.2 Period before measurements

A part of the growers does not experience anything of climate differences in their greenhouse, before the measurements are performed. This could be due to the fact that in two cases the measurements are started in a new build greenhouse. On the other hand, some growers sense the temperature differences by walking through the greenhouse.
The growers did in most cases not see any effect of the climate differences on the plant condition or production. This could be due to the fact that in two greenhouses with orchids the plants are on movable containers. In that case the plants do not stay for a long period on the same location with the bad climate conditions and all plants follow more or less the same path so it is difficult to detect differences in plant conditions. Another reason could be the fact that greenhouses with flowers (4 greenhouses) have many different breeds with makes it also difficult to see the effect of local climate conditions on the plants. Only two of the growers indicate that they had some problems with the production, like botrytis in a tomato plant and damage to the leafs of orchids. These problems were found in plants located in cold or wet spots.
Growers did already took several measures which should result in a more homogeneous climate before temperature measurements where performed. They did this during designing and constructing the greenhouse or during the time they were using the greenhouse. All greenhouses have fans for air circulation. Other measures to prevent cold spots near the walls, are better insulation of the walls, with the use of wall screens or ‘stegdoppelplaten’. During the night and during cold weather conditions also the roof screens are closed. The roof screens are also used for better insulation. Two of the growers build their relatively new greenhouse for “Het Nieuwe Telen (HNT)”. They use air handling units for drying and heating the air. Also two growers placed vertical partitions in the ridge to prevent cold airflow above the screen.
The reason for most of the growers to do measurements was to get insight in the climate differences. Another important reason is to get a better climate and save energy. Two growers did the measurements because they wanted to see how and whether HNT works. One grower did measurements, because he wanted to receive a green label.

## 4.3 During the measurements

The measured temperature inhomogeneity found in the greenhouses of the interviewed growers differs for each greenhouse. The location, size and temperature difference of the cold or hot spots are different. In two greenhouses the temperature differences where small about 1 K, greenhouses with tomato and peppers. In the other cases the temperature differences were larger on average about 3 K, but with peaks of 5 K.

The location of cold and hot spots in the greenhouse is different for each greenhouse. But often it is the case that cold spots are near the walls and hot spots are in the middle of the greenhouse. The locations and size of those spots could change during time. Also the magnitude of the temperature differences could chance with chancing conditions.

All growers said that with low outside temperatures the homogeneity will decrease. Also the effect of wind direction on homogeneity is given by the growers as an explanation for the location of the cold or hot spot. In general the wind direction will cause a relatively hot spot in the corner or side were the wind is coming from. On the other side of the greenhouse there is a cold spot. This is caused by air circulation due to suction of the wind. Next to this also the influence of the sun is mentioned by the growers. The sun could heat some parts of the greenhouse more than others parts due to differences in albedo or evaporation of the plants. But also the sun could heat up the sensors (something that is unintended) and in that way have influence on the measurements

Next to the metrological causes for temperature differences there are also technical and constructional causes mentioned by the growers. The most mentioned is the use of the screens, there is often cold air downdraught through the screen at the lowest point in the greenhouse. Also chinks in the screen allow cold air to flow and locally cool down the greenhouse temperature. Another important issue is the adjustment and design of the heating system. Sometimes valves are not working, which could cause too much or too less heating. In some greenhouses the wall heating is under the same control as the heating inside the greenhouse. Another cause is the cooling down of heating water in the pipes when the hot water flows through the pipes. Near the supply pipes the water is relatively hot which result in hot spots. It is also possible that during the design the heating capacity is not calculated correctly, which could result in too much or too less heating on certain locations. If the configuration of the fans is not correct, the temperature distribution in the greenhouse is also negatively influenced.

## 4.4 After the measurements

After and during the measurements measures are taken by the growers to increase the homogeneity. The influence of the metrological and technical causes should be limited, to increase the homogeneity. Here the most important measures will be discussed.

The most frequent measure was to close the screen more often for 100%. This should limit the flow of cold air through the chinks and the influence of the outside temperature is less. Some growers installed vertical partitions (some did already have them) which will stop the airflow above the screen and limit the downdraught at the lowest point of the greenhouse. The supply pipes and some of the heating pipes in hot spots are insulated with insulating paint, this will locally reduce the heating capacity. In cold spots sometimes extra pipes are installed. To prevent fluctuations in temperature and to create homogeneity some growers constantly set the growingpipe on a low temperature. When the configuration of the fans was not correct, this was also changed.

The growers confirmed that the effect of the different measures resulted in an improvement of the homogeneity. The size of this improvement is different for each greenhouse. The growers with diseases in their vegetation also experienced no more or less frequent diseases.

Nearly all growers are saying or thinking that with the increasing homogeneity due to the measures their energy use should decrease. But they have in general no data to support this.

There is only one grower who could show the energy use over the recent years. In figure 4.1 an overview is given of the energy use of the greenhouse. On the left y-axis the energy use, natural gas combined with electricity use and delivered electricity, in MJ/m$^2$ per week is given. The lines represent the cumulative energy use on the right y-axis. This grower reduced his energy use from 2500 MJ/m$^2$ in 2010 till 1800 MJ/m$^2$ in 2013 by taken multiple measures to save energy and to improve homogeneity. This is a reduction of about 28 percent. This saving is not only reached by increasing the homogeneity, but also be taken other energy saving measures.

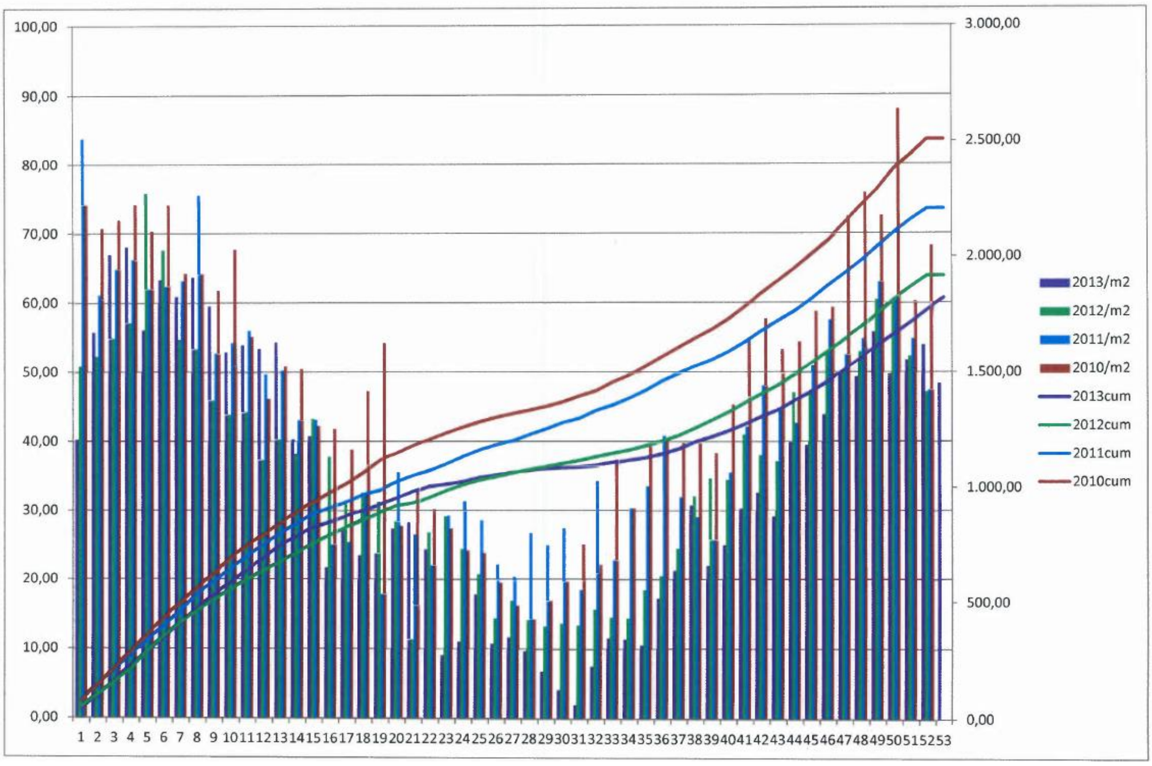


**Figure 4.1: Energy use, natural gas combined with electricity use and delivered electricity over the year per week and cumulative**

The growers admit that with a more uniform greenhouse climate, it is easier to control the climate. A more uniform climate could allow the grower to shrink their margins of the temperature and VD settings of the climate computer. It makes it possible to grow closer to the minimum temperatures and VD. Growers will only do this, if they are very sure that there is a homogenous climate and that it has no negative effect on production.

Only one of the eight interviewed growers changed something in the climate settings of his climate computer. Initially the minimum VD was 2,5 g/m$^3$ this was changed to 1,7 g/m$^3$.

The growers are satisfied with the insight a wireless sensor network give in their greenhouse climate. As a negative point the high uncertainty at relative humidity above 95% is mentioned. Some growers want to perform more (or again) measurements. Some also want to measure more variables. Growers are planning more measures, because climate homogeneity is a continuous improvement process.

## 4.5 Conclusions interviews

After the eight interviews the following points are clear:

- Each greenhouse has its own specific problems with homogeneity, the location, size and temperature difference of the cold or hot spots are different. But in most cases the low temperatures were found near the walls of the greenhouse.

- There is not one specific cause for inhomogeneity. There are metrological causes/influencing factors like: outside temperature, wind speed, wind direction and the sun. There are also technological causes: downdraught, chinks in the screen, not correctly working heating system.
- The most important measures used by the growers to increase homogeneity are: totally closing the screen, insulating, vertical partitions above the screen and optimizing heating systems.
- Growers are satisfied with the insight wireless sensors gives in the greenhouse climate. The sensors give good insight in where hot and cold places are, this helps to do a more targeted search for the causes
- Growers are saying that a more homogeneous climate should result in less energy use. But unfortunately most of them have no data to support their statement. The grower which could show data of his energy use showed a reduction in energy use of about 28 percent in 3 years, but this was not only by increasing the homogeneity.
- Growers will not change their climate setpoints if this has a possible negative effect on their production.

# 5 Results data analysis

In this chapter the data analysis of the climate data will be described. Greenhouse 1 is the greenhouse in which new measurements are performed. The other analyse is done for one of the existing datasets.

## 5.1 Greenhouse 1

Greenhouse 1 has a size of about 3 hectares (190m*160m). The 12 span greenhouse has a ridge height of 8m and a gutter height of 5m. The greenhouse has five departments, department 1 till 4 are from east to west and department 5 is the part in north, in which the production area is. Measurements are done in departments 2 and 3. In figure 5.1 an aerial view of the greenhouse is given.

**Figure 5.1: Aerial view of greenhouse 1**

In the greenhouse Kalanchoë are cultivated, on movable tables of about 1 m height, which is visible in figure 5.2. The greenhouse uses sunscreens above certain radiation fluxes (between 300-400 W/$m^2$ different for each screen). An energy/blackout screen is used during night times, the dark time is 14 hours and starts at 18:30. Also side screens are present.

**Figure 5.2: The inside of the greenhouse**

Along the total length of the ridges and on both sides of the ridges windows are used for ventilation. For heating, pipes above and beneath the tables are used. In figure 5.3 the heating and ventilation strategies are shown. These temperatures are not static they will be slightly lower when solar radiation is higher. The Priva climate computer will control the heating and ventilation in such a manner that the temperature should stay between the two lines. The drop of the heating and ventilation temperatures in the morning is to arrange that the plants will limits its height grow. In this way the Kalanchoë will stay compact and have a better quality.

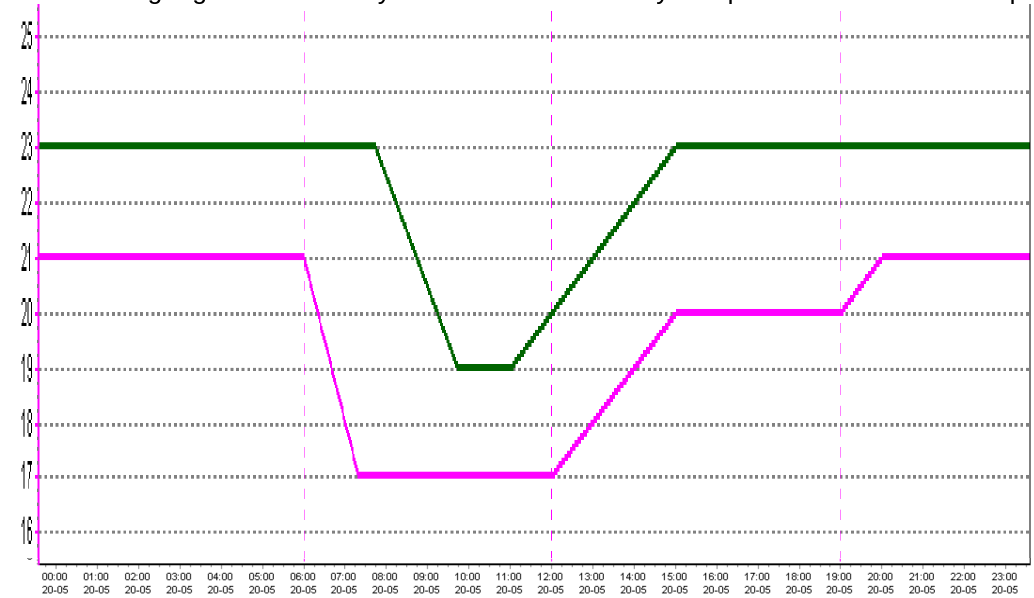


**Figure 5.3: Heating(pink) and ventilation(green) temperatures during the day.**

Fans are used to distribute the air through the greenhouse, which should create a more homogeneous climate, fans are generally on when measured temperature differences are larger than one Kelvin. Recently three air treatment units (Eco Climate Converter, ECC) are placed at the south side wall of the greenhouse in departments 2, 3 and 4. These units will dry the inside air and reuse latent heat. But they could also blow heat extracted from the heating system. The ECC's will be on when the vapour deficit is lower than 4,5 g/m3, this is mainly during the night.

In case of temperatures above 27 degree Celsius, vaporizers are used for cooling. They could also be used when the relative humidity is very low.

### *5.1.1 Measurements*

There are temperature and relative humidity measurements done on two vertical levels. One 4*3 sensor grid on plant level about 30 cm above the table. And the second 4*3 sensor grid is on fan level about 2,5 m above the table. There is also a sensor placed at inlet(#5) and one at the outlet(#4) of the ECC. This is shown in the map in figure 5.4.

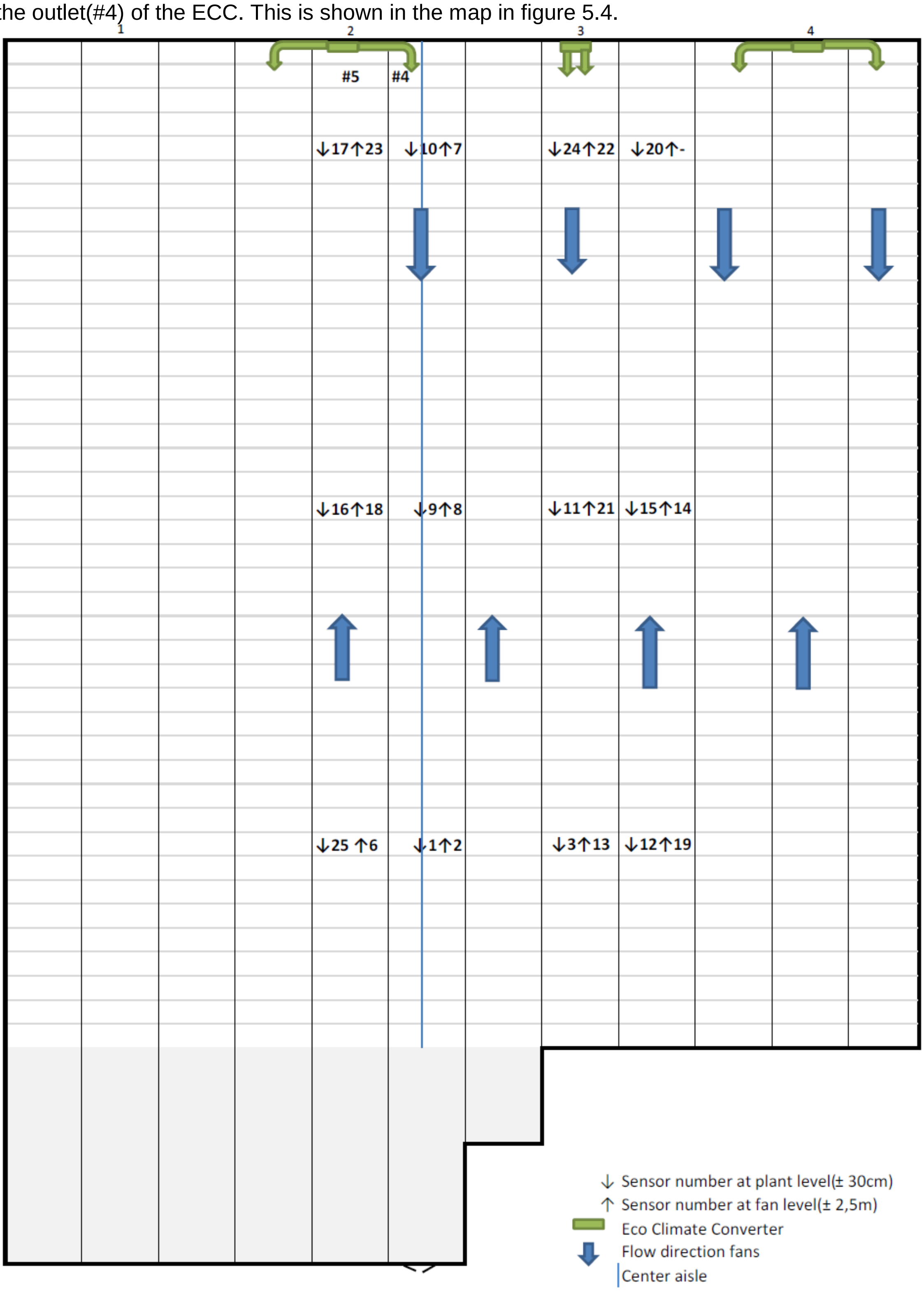


**Figure 5.4: Map of the greenhouse with sensor locations**

### *5.1.2 Measured inhomogeneity*

In figure 5.5 the average temperature differences during the day for the spring period 15-4-2014 till 26-5-2014 of a five minute interval are given. The largest effect on homogeneity is visible when the energy screen is closed or opened. During the night the inhomogeneity is on average 1,3 K on plant level and 2,2 on fan level. During the day the temperature difference on plant level is on average 2,8 K and 2,5 K on fan level. So during the day the inhomogeneity on plant level is higher and during the night on fan level higher temperature differences are found.

Visible is that the inhomogeneity increases when the screen is opened and decreases when the screen is closed. When the screen is closed and the ECC is off the inhomogeneity is about 1,1 K on both plant and fan level. On fan level the homogeneity is strongly influenced by the ECC, because a few sensors are relatively close to the outlet off the ECC and receive the hot air from the ECC. The dT will increase to about 2,2 K on fan level when the ECC is on. The effect of the ECC on plant level is small, the increase in inhomogeneity is only 0,3 K. During the day the inhomogeneity is fluctuating, even the average values over a month show fluctuations.

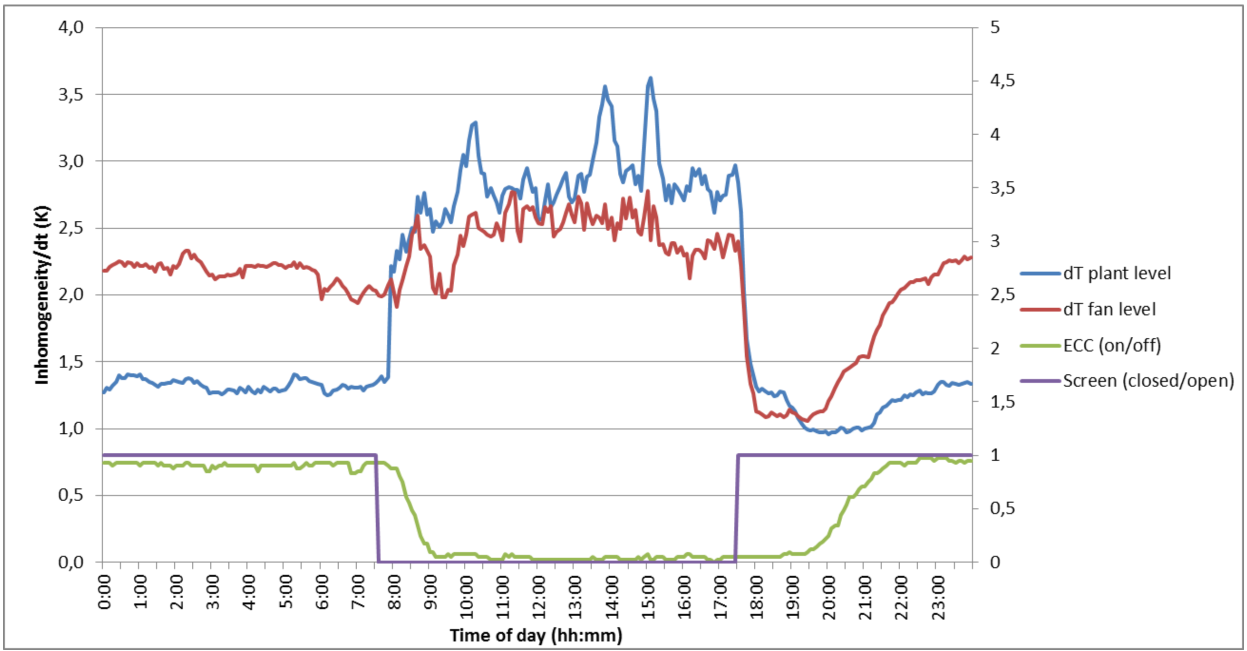


**Figure 5.5: Average temperature differences and the average condition of ECC and screen during the day over the measurement period**

### *5.1.3 Relations factors and inhomogeneity*

From the climate computer several variables are investigated for a relation with the inhomogeneity. Which are meteorological variables like outside temperature, rain, wind speed, wind direction, solar radiation. Also variables which are controlled by the climate computer like heating, energy screen, ECC, ventilation.

Table 5.1 gives the correlation map of all different factors which could have an influence on the inhomogeneity, this is based on the all the data. If there is a correlation it does not mean that there is causality between the factors. The screen has the strongest correlation with the inhomogeneity, which could also be concluded from figure 5.5. There is a strong negative correlation between the screen and inhomogeneity. With increasing screen (screen is closing) the inhomogeneity is lower. There is also a strong correlation with solar irradiance, this correlation is positive. Which means with more solar irradiance the inhomogeneity of the greenhouse climate is higher. The correlation between outside temperature and inhomogeneity is also positive. The factor inside-outside T is the difference between the inside

and the outside temperature is which also has a correlation. All heated related factors like pipe temperatures have strong negative correlation with inhomogeneity. So when the heating is becoming higher the inhomogeneity is in general lower.
The factors with strong correlation with inhomogeneity, mentioned above, also have a correlation with each other.
The ventilation factors, which are the openings of the windows, have a moderate positive correlation.

| | *Inhomogeneity* | *Inside Temperature* | *Outside Temperature* | *Inside-outside T* | *Solar irradiance* | *Wind speed* | *wind direction* | *Raiun* | *Screen* | *ECC* | *Relative humidity* | *Vapout deficit* | *Ventilation windward* | *Ventilation leeward* | *Pipe temperature1* | *Pipe temperature2* | *Heating* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Inhomogeneity | | | | | | | | | | | | | | | | | |
| Inside Temperature | 0,09 | | | | | | | | | | | | | | | | |
| Outside Temperature | 0,66 | 0,56 | | | | | | | | | | | | | | | |
| Inside-outside T | -0,65 | 0,37 | -0,56 | | | | | | | | | | | | | | |
| Solar irradiance | 0,73 | 0,41 | 0,85 | -0,55 | | | | | | | | | | | | | |
| Wind speed | 0,45 | 0,41 | 0,65 | -0,32 | 0,52 | | | | | | | | | | | | |
| wind direction | -0,11 | -0,17 | -0,18 | 0,04 | -0,14 | -0,26 | | | | | | | | | | | |
| Raiun | -0,09 | -0,14 | -0,13 | 0,01 | -0,06 | 0,03 | -0,04 | | | | | | | | | | |
| Screen | -0,83 | -0,05 | -0,70 | 0,74 | -0,77 | -0,44 | 0,12 | 0,01 | | | | | | | | | |
| ECC | -0,22 | -0,40 | -0,43 | 0,08 | -0,44 | -0,33 | 0,11 | -0,13 | 0,34 | | | | | | | | |
| Relative humidity | -0,58 | -0,59 | -0,82 | 0,34 | -0,80 | -0,61 | 0,22 | 0,04 | 0,68 | 0,70 | | | | | | | |
| Vapout deficit | 0,51 | 0,74 | 0,84 | -0,20 | 0,78 | 0,61 | -0,21 | -0,08 | -0,60 | -0,66 | -0,98 | | | | | | |
| Ventilation windward | 0,31 | 0,18 | 0,19 | -0,03 | 0,19 | 0,17 | -0,02 | 0,03 | -0,21 | -0,11 | -0,22 | 0,24 | | | | | |
| Ventilation leeward | 0,55 | 0,47 | 0,71 | -0,33 | 0,67 | 0,50 | -0,14 | -0,01 | -0,52 | -0,42 | -0,77 | 0,77 | 0,36 | | | | |
| Pipe temperature1 | -0,65 | -0,28 | -0,89 | 0,72 | -0,77 | -0,57 | 0,09 | 0,07 | 0,72 | 0,30 | 0,65 | -0,63 | -0,16 | -0,60 | | | |
| Pipe temperature2 | -0,70 | -0,30 | -0,86 | 0,66 | -0,80 | -0,56 | 0,13 | 0,10 | 0,73 | 0,18 | 0,65 | -0,64 | -0,16 | -0,63 | 0,90 | | |
| Heating | -0,71 | -0,27 | -0,85 | 0,69 | -0,81 | -0,55 | 0,08 | 0,07 | 0,77 | 0,31 | 0,69 | -0,66 | -0,17 | -0,63 | 0,89 | 0,96 | |

**Table 5.1: Correlation map of all data**

It is more interesting to look at the inhomogeneity during the night and/or when the screen is closed. Then there is no influence of the sun on the sensors. During the night also the most critical moments are reached regarding risks of diseases, because low temperature and high relative humidity. A new correlation map is created to investigate whether there are any correlations between the influencing factors and inhomogeneity when there is less than one W/m$^2$ solar irradiance.

In table 5.2 the correlation map is shown when there is very less or none solar irradiance. In contrast with the correlation map of all data there are no strong correlations with inhomogeneity. There is a weak positive correlation with the ECC. When the ECC is on the inhomogeneity is higher in general. In the correlation map with all data, the correlation between the ECC and inhomogeneity was the opposite, a weakly negative correlation. With wind speed there is weak negative correlation. This indicates that with higher wind speeds the temperature differences inside the greenhouse will be lower. This is an unexpected result. In the correlation map with all data, the correlation between wind speed and inhomogeneity was positive.

The strong correlation between the heated related factors and inhomogeneity also disappeared. Only the temperature of pipe2 shows a weak negative correlation with inhomogeneity.

Visible is that during night times none of factors show a strong correlation with inhomogeneity. This could be due to the fact that that the average inhomogeneity is low about 1 K during the night. During the day when the blackout screen is open and ventilation windows are open there is no well insulated greenhouse anymore. This means that during the day the outside climate could have a bigger influence on the greenhouse climate.

| | *Inhomogeneity* | *Inside Temperature* | *Outside Temperature* | *Inside-outside T* | *Solar irradiance* | *Wind speed* | *wind direction* | *Raiun* | *Screen* | *ECC* | *Relative humidity* | *Vapout deficit* | *Ventilation windward* | *Ventilation leeward* | *Pipe temperature1* | *Pipe temperature2* | *Heating* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Inhomogeneity | | | | | | | | | | | | | | | | | |
| Inside Temperature | -0,08 | | | | | | | | | | | | | | | | |
| Outside Temperature | 0,04 | 0,16 | | | | | | | | | | | | | | | |
| Inside-outside T | -0,06 | 0,07 | -0,97 | | | | | | | | | | | | | | |
| Solar irradiance | -0,03 | -0,01 | 0,04 | -0,04 | | | | | | | | | | | | | |
| Wind speed | -0,21 | 0,11 | 0,17 | -0,14 | 0,12 | | | | | | | | | | | | |
| wind direction | 0,00 | 0,06 | 0,05 | -0,04 | 0,06 | 0,10 | | | | | | | | | | | |
| Raiun | -0,09 | 0,08 | 0,06 | -0,04 | 0,09 | 0,17 | 0,12 | | | | | | | | | | |
| Screen | -0,04 | 0,24 | -0,14 | 0,20 | -0,07 | -0,06 | -0,04 | -0,02 | | | | | | | | | |
| ECC | 0,32 | -0,05 | 0,08 | -0,09 | -0,02 | -0,06 | -0,02 | -0,15 | -0,01 | | | | | | | | |
| Relative humidity | 0,02 | -0,38 | 0,56 | -0,66 | 0,07 | 0,15 | 0,15 | 0,08 | -0,26 | 0,21 | | | | | | | |
| Vapout deficit | -0,04 | 0,47 | -0,52 | 0,64 | -0,06 | -0,12 | -0,13 | -0,07 | 0,27 | -0,20 | -0,99 | | | | | | |
| Ventilation windward | -0,04 | 0,13 | 0,07 | -0,04 | 0,04 | 0,04 | -0,01 | 0,05 | 0,01 | -0,10 | -0,10 | 0,14 | | | | | |
| Ventilation leeward | -0,06 | 0,19 | 0,13 | -0,09 | 0,00 | 0,02 | -0,04 | 0,01 | 0,01 | -0,15 | -0,09 | 0,14 | 0,55 | | | | |
| Pipe temperature1 | 0,06 | 0,26 | -0,57 | 0,63 | -0,05 | -0,06 | -0,04 | -0,08 | 0,13 | 0,01 | -0,66 | 0,66 | -0,05 | -0,09 | | | |
| Pipe temperature2 | -0,24 | 0,22 | -0,69 | 0,75 | -0,05 | -0,11 | -0,08 | -0,04 | 0,15 | -0,32 | -0,66 | 0,65 | -0,04 | -0,07 | 0,66 | | |
| Heating | 0,00 | -0,63 | -0,50 | 0,36 | -0,01 | -0,26 | -0,14 | -0,10 | -0,12 | -0,17 | -0,15 | 0,08 | -0,05 | -0,07 | 0,23 | 0,35 | |

**Table 5.2: Correlation map of data if solar irradiance <1 W/m$^2$**

In appendix III the effect of three weather conditions (temperature, solar irradiance and wind speed) is investigated. A day with cold temperatures is compared with a day with hot temperatures while the two other weather factors are comparable for those days. This is also done for a sunny day compared with a cloudy day and day with high wind speeds compared with a day with low wind speeds.

In figure 5.6 the average inhomogeneity for each measured outside temperature is shown. Looking at the relation between the outside temperature and inhomogeneity in figure 5.6 there is not a significant relation. There seem to be a higher inhomogeneity with higher outside temperatures. By taking a look at the extreme day comparison in appendix III the inhomogeneity of the hot day looks slightly higher. During day time when the screen is open there is no difference in homogeneity.

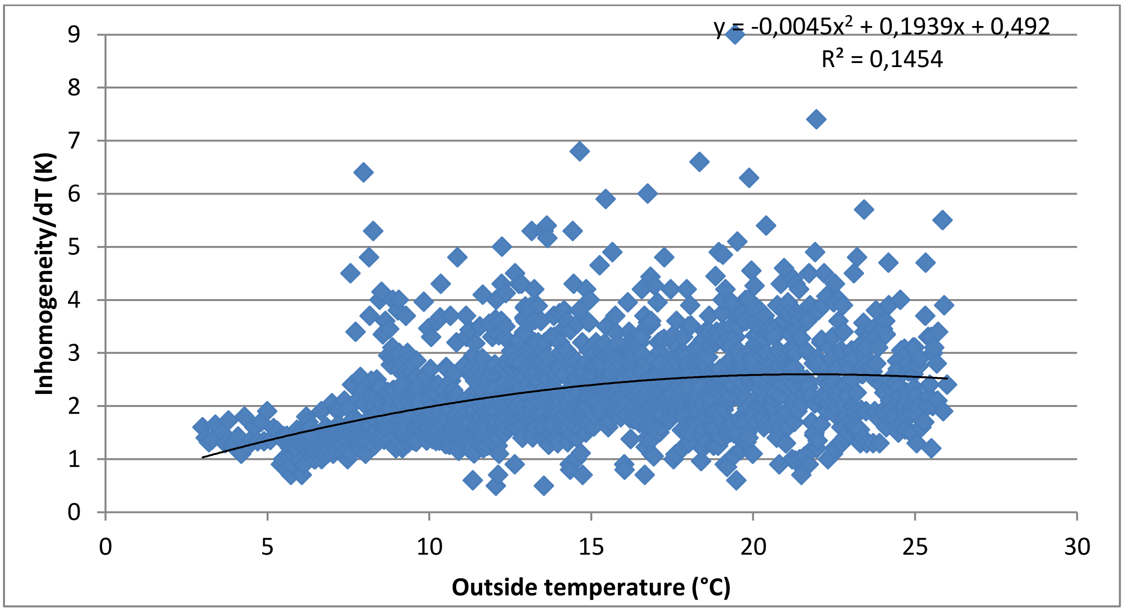


**Figure 5.6: Average dT for each measured outside temperature**

In figure 5.7 the average inhomogeneity for each measured solar radiation is given. Solar radiation shows a stronger relation with inhomogeneity than outside temperature. This could due to the fact that solar radiation has a larger reach between 0 and 1000 W/m$^2$ and temperature between 5 and 25 °C. This relation also has to do with the difference between day and night. During the night screens and windows are closed and the temperature difference inside the greenhouse is about 1 K. This relation is also visible in Appendix III on the sunny day the inhomogeneity was about 3,5 K and on the cloudy day it was around 2,5 K.

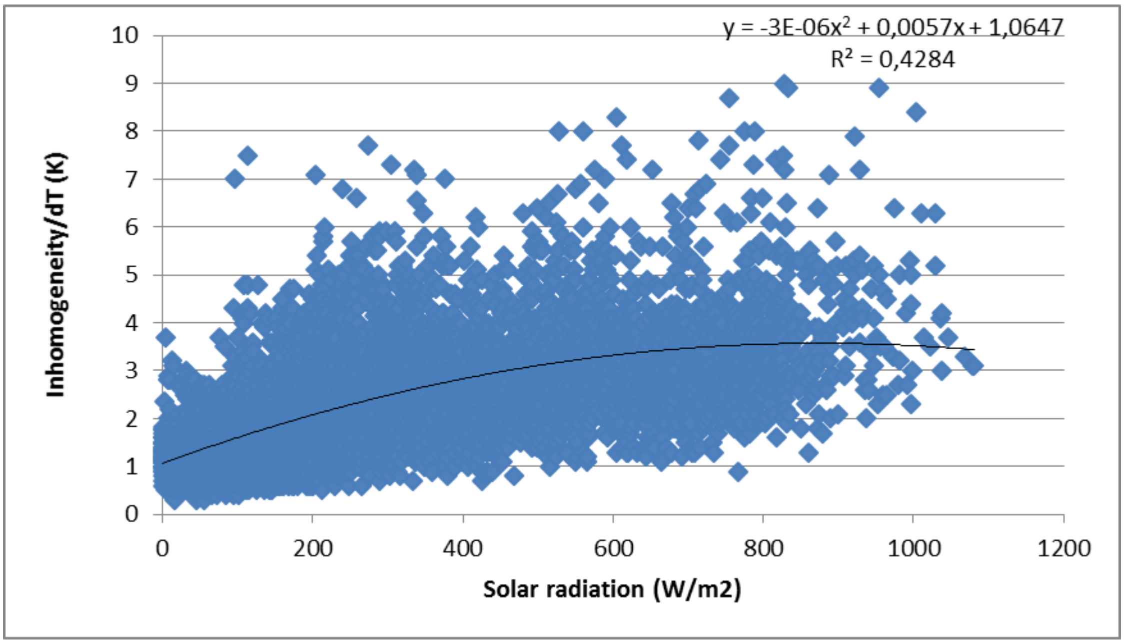


**Figure 5.7: Average dT for each measured solar radiation**

In figure 5.8 a spider diagram is shown in which for different wind speeds categories the average inhomogeneity is given for different wind directions. All lines are close together around 2 K. The exception is a wind coming from the north stronger than 3 m/s in that cases the average inhomogeneity is larger than 3 K. Also wind blowing from the south gives higher inhomogeneity. This has probably something to do with the orientation of the greenhouse which is also north-south. The wind speed categories with higher wind speeds show also slightly higher inhomogeneity. In appendix III there is no difference during night time between the day with high and the day with low wind speed. During the day with high wind speed the inhomogeneity shows great variation up to 6 K. In contrast with the day of low wind speeds when the inhomogeneity is fluctuating between 2 and 4 K.

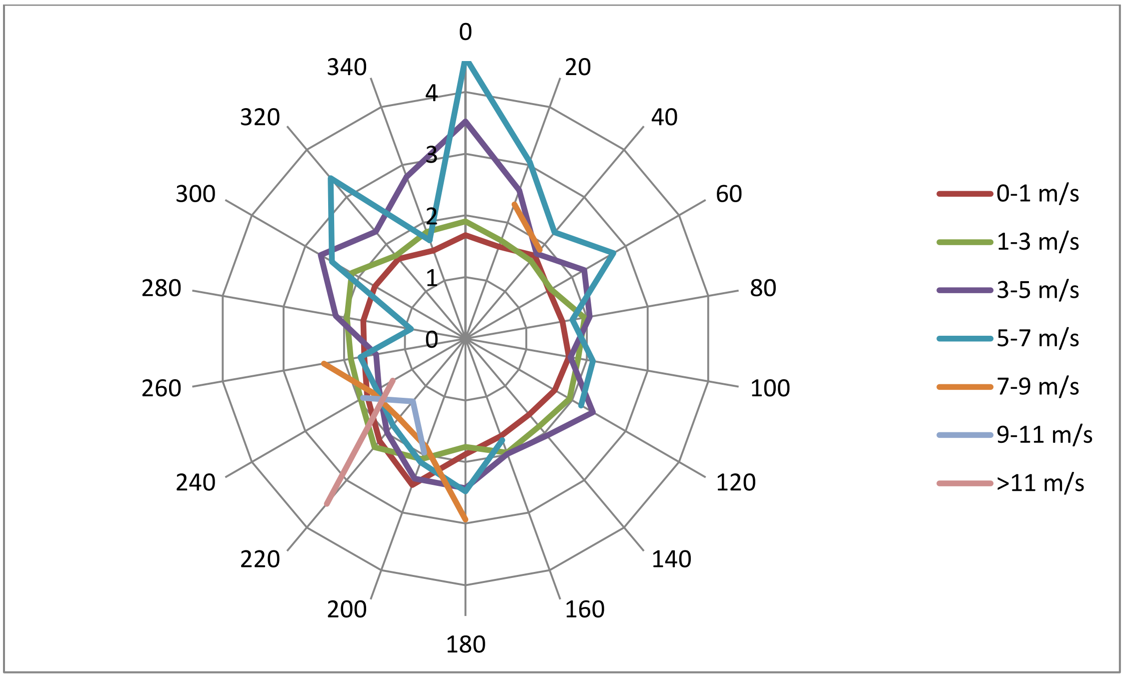


**Figure 5.8: A spider diagram with average inhomogeneity for different wind directions divided in wind speeds categories**

Clear is that during the night when screen and windows are closed there is no or very less influence from the outside conditions on the climate inhomogeneity inside. During the day the screens and windows are open and the outside temperature, sun and wind could influence the inside climate.

## 5.2 Greenhouse 2

Greenhouse 2 is a greenhouse with tomato plants build in 2011. It has a size of two hectares and it is subdivided in two departments. The aisle is in the north part which is visible in figure 5.9. The greenhouse has a double screen. The heating is done with the use growing pipes and there is a separate system for the heating near the walls. The walls are insulated with the use of stegdoppelplaten. The greenhouse is built for “het nieuwe telen” and therefore has air handling units(AHU) which dry and heat the air. The AHU’s could switch between inside and outside air. The air is distributed with the use of air hoses (Wientjens, 2013).

In figure 5.9 the locations of the wireless sensors are given. The sensors are distrusted in a 4*6 grid. Sensor 25 is located near the measurement box of the greenhouse to serve as a reference.

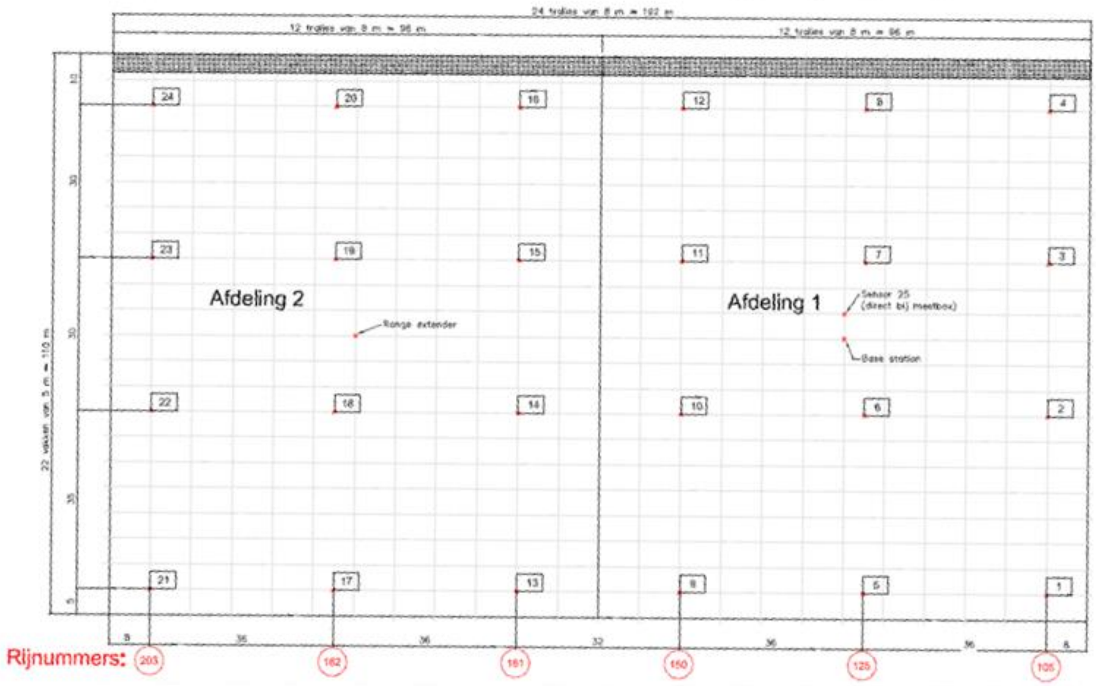


**Figure 5.9: Map of the greenhouse with sensor locations (Wientjens, 2013)**

### 5.2.1 *Measured inhomogeneity*

In figure 5.10 the average inhomogeneity during a day over the measurement period is given. The measurement period was in the winter from 6-1-2013 till 3-3-2013. Also the average closing percentages of the screens are given. Visible is that during the night the inhomogeneity is stable around 3 K. During the day from 8 o’clock the temperature differences increase gradually till on average 5,2K between 14 and 15 o’clock. After a gradual decrease, around 19 o’clock the inhomogeneity is again on the night level. There is not a sudden large change visible when looking at the day and night time. This is probably caused by the fact that the screens are not closed during fixed periods, but the screens are controlled based on climate conditions.

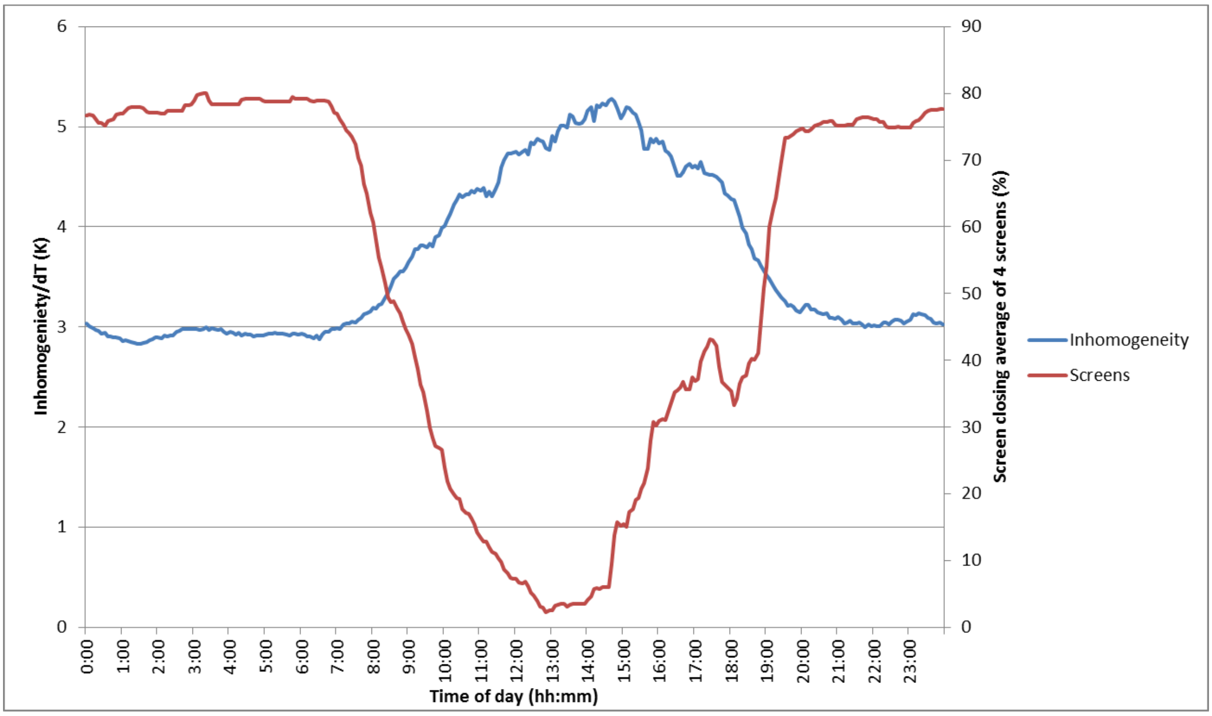


**Figure 5.10: Average temperature differences and the average closing of the screens during a day over the measurement period**

### 5.2.2 *Relations factors and inhomogeneity*

In table 5.3 the correlation map of all data with different factors for greenhouse 2 is given. The strongest correlations with inhomogeneity will be discussed here. There are moderate positive correlations with vapour deficit (VD), solar irradiance and inside temperature. This follows logical from figure 5.10 in which visible is that during the day the inhomogeneity is higher. This correlation could be explained because the factors VD, solar irradiance and inside temperature are also higher during the day. There is a moderate negative correlation between the percentage of outside air used by the AHU and the inhomogeneity.

| | *Inhomogneity* | *Inside Temperature* | *Outside Temperature* | *Inside-outside T* | *Solar irradiance* | *Wind speed* | *Wind direction* | *Rain* | *Screen* | *AHU speed* | *AHU outside air* | *AHU inside air* | *VD* | *Ventilation leeward* | *Ventilation windward* | *Pipe temperature* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Inhomogneity | | | | | | | | | | | | | | | | |
| Inside Temperature | 0,49 | | | | | | | | | | | | | | | |
| Outside Temperature | -0,12 | -0,01 | | | | | | | | | | | | | | |
| Inside-outside T | 0,41 | 0,66 | -0,76 | | | | | | | | | | | | | |
| Solar irradiance | 0,51 | 0,59 | 0,13 | 0,29 | | | | | | | | | | | | |
| Wind speed | 0,08 | 0,08 | 0,26 | -0,15 | 0,07 | | | | | | | | | | | |
| Wind direction | -0,01 | -0,12 | 0,49 | -0,45 | -0,04 | 0,03 | | | | | | | | | | |
| Rain | -0,01 | 0,00 | 0,05 | -0,04 | -0,02 | 0,11 | 0,02 | | | | | | | | | |
| Screen | -0,36 | -0,30 | -0,58 | 0,24 | -0,51 | -0,22 | -0,29 | -0,02 | | | | | | | | |
| AHU speed | -0,28 | 0,05 | 0,00 | 0,03 | -0,08 | 0,11 | -0,07 | 0,02 | 0,24 | | | | | | | |
| AHU outside air | -0,46 | -0,21 | 0,13 | -0,23 | -0,24 | 0,04 | 0,00 | 0,03 | 0,30 | 0,62 | | | | | | |
| AHU inside air | 0,41 | 0,20 | -0,10 | 0,21 | 0,25 | 0,01 | 0,01 | -0,03 | -0,32 | -0,49 | -0,97 | | | | | |
| VD | 0,53 | 0,84 | -0,10 | 0,62 | 0,55 | 0,01 | -0,11 | -0,01 | -0,25 | -0,19 | -0,22 | 0,15 | | | | |
| Ventilation leeward | -0,01 | -0,20 | 0,49 | -0,50 | 0,06 | 0,10 | 0,27 | 0,00 | -0,35 | -0,23 | -0,13 | 0,15 | -0,19 | | | |
| Ventilation windward | -0,04 | -0,25 | 0,35 | -0,43 | -0,03 | -0,01 | 0,23 | -0,02 | -0,26 | -0,30 | -0,13 | 0,15 | -0,21 | 0,89 | | |
| Pipe temperature | 0,39 | 0,74 | -0,05 | 0,52 | 0,34 | 0,13 | -0,11 | 0,01 | -0,32 | -0,07 | -0,19 | 0,17 | 0,63 | -0,21 | -0,20 | |

**Table 5.3: Correlation map of all data**

Again a new correlation map is created with low solar irradiance to exclude the effect of solar irradiance on the temperature measurements. This correlation map shows the correlations which are found during the night. The strongest correlation with homogeneity during the night is a negative correlation (-0,39) with the percentage of outside air used by the AHU. When a higher percentage of outside air is used the inhomogeneity is lower. The is also a weak negative correlation with the ventilation speed of the AHU. With higher ventilation speed the inhomogeneity is lower. The outside temperature has also a weak negative correlation with the inhomogeneity. From the correlations in table 5.4 an assumption could be made that during nights with low outside temperatures the inhomogeneity is higher. When the AHU wants to lower the relative humidity on high capacity (higher speed and with a high percentage of outside dry air) the inhomogeneity is lower.

| | *Inhomogneity* | *Inside Temperature* | *Outside Temperature* | *Inside-outside T* | *Solar irradiance* | *Wind speed* | *Wind direction* | *Rain* | *Screen* | *AHU speed* | *AHU outside air* | *AHU inside air* | *VD* | *Ventilation leeward* | *Ventilation windward* | *Pipe temperature* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Inhomogneity | | | | | | | | | | | | | | | | |
| Inside Temperature | 0,06 | | | | | | | | | | | | | | | |
| Outside Temperature | -0,33 | -0,29 | | | | | | | | | | | | | | |
| Inside-outside T | 0,29 | 0,63 | -0,92 | | | | | | | | | | | | | |
| Solar irradiance | -0,08 | 0,08 | -0,02 | 0,05 | | | | | | | | | | | | |
| Wind speed | -0,06 | -0,06 | 0,29 | -0,26 | 0,02 | | | | | | | | | | | |
| Wind direction | -0,12 | -0,25 | 0,55 | -0,55 | -0,04 | 0,06 | | | | | | | | | | |
| Rain | -0,01 | -0,01 | 0,06 | -0,05 | 0,05 | 0,11 | 0,04 | | | | | | | | | |
| Screen | -0,02 | 0,44 | -0,75 | 0,79 | 0,03 | -0,25 | -0,46 | -0,06 | | | | | | | | |
| AHU speed | -0,36 | 0,4 | 0,03 | 0,13 | 0,08 | 0,15 | -0,04 | 0,02 | 0,25 | | | | | | | |
| AHU outside air | -0,39 | 0,27 | 0,29 | -0,12 | 0,06 | 0,09 | 0,11 | 0,05 | 0,09 | 0,67 | | | | | | |
| AHU inside air | 0,29 | -0,3 | -0,25 | 0,08 | -0,05 | -0,03 | -0,09 | -0,05 | -0,13 | -0,55 | -0,96 | | | | | |
| VD | 0,21 | 0,78 | -0,29 | 0,55 | 0,01 | -0,12 | -0,19 | -0,01 | 0,39 | 0,09 | 0,25 | -0,37 | | | | |
| Ventilation leeward | -0,05 | -0,35 | 0,58 | -0,61 | -0,04 | 0,14 | 0,33 | -0 | -0,55 | -0,31 | -0,17 | 0,2 | -0,32 | | | |
| Ventilation windward | -0,04 | -0,36 | 0,46 | -0,52 | -0,04 | 0,01 | 0,29 | -0,02 | -0,48 | -0,38 | -0,2 | 0,22 | -0,31 | 0,91 | | |
| Pipe temperature | 0,24 | 0,61 | -0,17 | 0,38 | -0,01 | 0,06 | -0,13 | -0 | 0,14 | 0,14 | 0,07 | -0,11 | 0,55 | -0,15 | -0,1 | |

**Table 5.4: Correlation map of data if solar irradiance <1 W/m**

In figure 5.11 a scatterplot of the average inhomogeneity for each measured outside temperature is given. Visible is that the average temperature difference inside the greenhouse does not depend much on the outside temperature. The most data points are in the range between 2,5 and 5 K inhomogeneity. It looks like that with higher temperatures above 12 °C the temperatures difference will be lower. Even for low temperatures of lower than 0 °C there is no effect visible on the inhomogeneity.

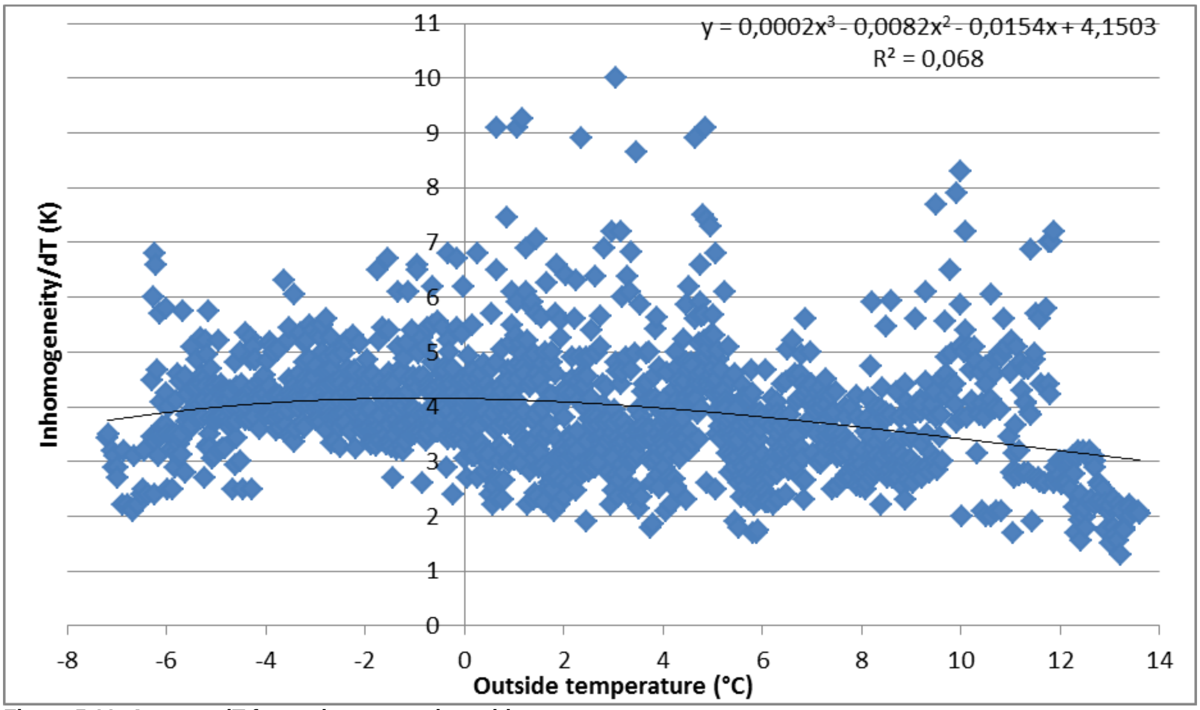


**Figure 5.11: Average dT for each measured outside temperature.**

In figure 5.12 the effect of the solar irradiance on the inhomogeneity is shown in a scatter plot. The average inhomogeneity is higher when the solar irradiance is higher. During the night with no solar irradiance the inhomogeneity is on average 4 K. During the day the inhomogeneity is higher, which was also visible in figure 5.10.

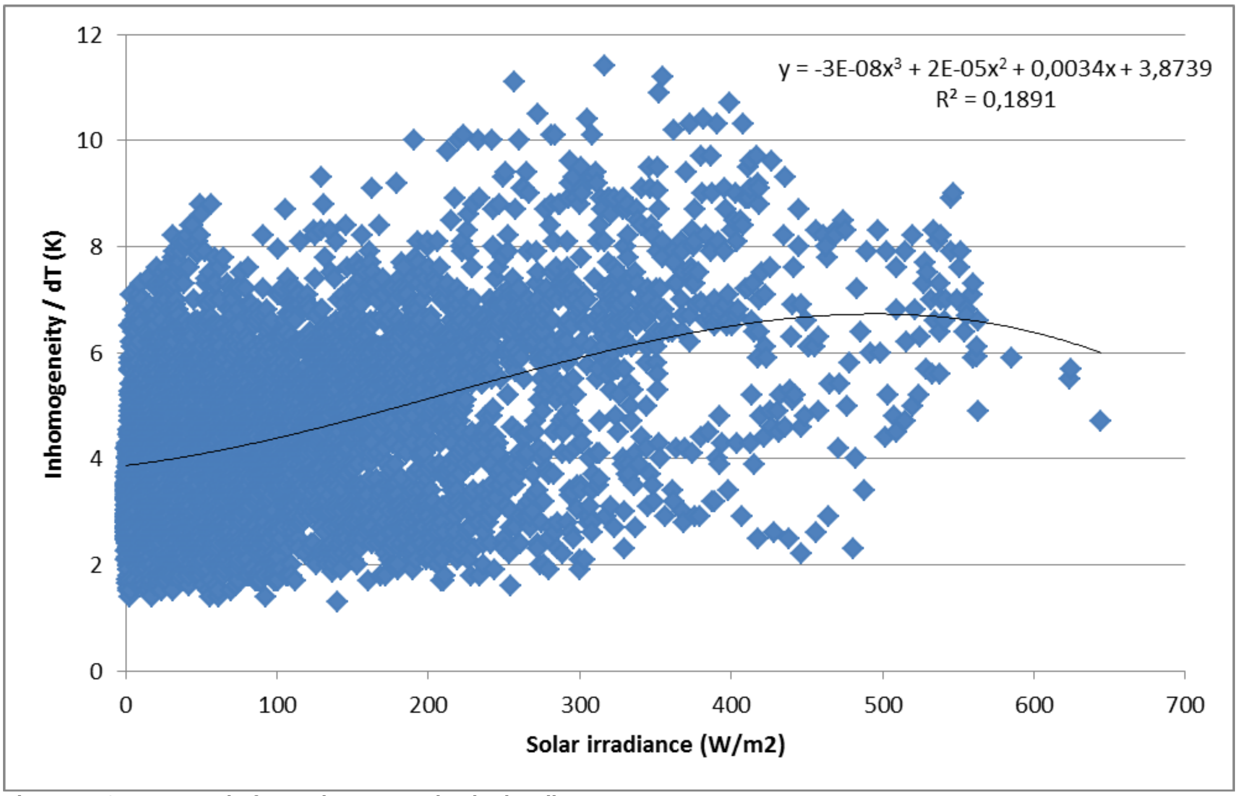


**Figure 5.12: Average dT for each measured solar irradiance**

In figure 5.13 the effect of wind speed and wind direction on inhomogeneity is shown. In this spider diagram the average inhomogeneity for different winds speed categories is given. Visible is that in general at lower wind speeds the inhomogeneity is also lower. When there is nearly any wind the inhomogeneity is on average 3,5 K. At high wind speeds of 5 m/s and higher the inhomogeneity is on average 4 K. There is also an effect visible of the wind direction. When the wind is coming from the east and southeast the average inhomogeneity is higher.

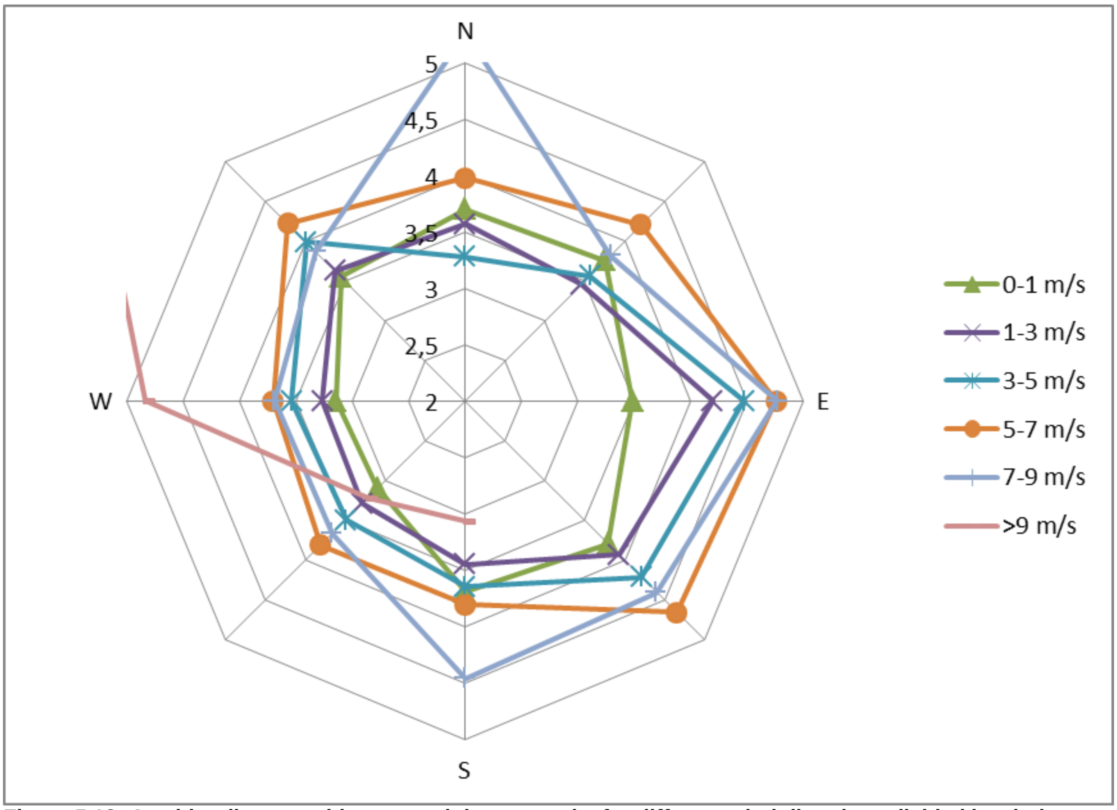


**Figure 5.13: A spider diagram with average inhomogeneity for different wind directions divided in wind speeds categories**

# 6 Discussion

In this chapter the results and assumptions of this research will be critically discussed. There will be started with a critical look at the literature study flowed by a look on the interviews. Finally the data analysis will be discussed.

## 6.1 Literature

In the literature which was found the only relation between energy use and inhomogeneity was found in an article of Esmeijer & Nijs (2000). The relation was 10% energy saving by reducing the temperature setpoint with 1 K for a greenhouse with tomatoes. How this is calculated is not shown in the article. Writers of other articles refer to this article and use it as rule of thumb. A research by De Zwart (2014) gives a relation between allowing higher relative humidity and energy use. With only these two references it is not possible to give a quantitative relation for inhomogeneity and energy use in common.

The results of studies which are presented in the literature study chapter are mostly studies done in one greenhouse. This means that the results are not applicable for all other greenhouses because every greenhouse is different. But the main factors which could cause climate inhomogeneity are found in multiple studies.

The literature study has shown that the use of WSN is quite new and still needs improvements.

## 6.2 Interviews

The interviews were only answered by a small group of eight growers. It would be better if the interviews were answered by a larger group of growers. But the group of growers which performed homogeneity measurements is not that large.

By processing the results of the interviews there is not made any difference is the kind or size of the greenhouse. This could result in some unreliable results.

The most important reason for the interviews was to hear from growers how their energy use changed when they improved the homogeneity. Unfortunately there was only one grower who could show some data of his energy use. Therefore and because of the lack of literature it is very difficult to give the quantitative relation between energy use and inhomogeneity.

Most growers think that a homogenous should result in less energy use but they cannot support this with data. One of the solutions for climate inhomogeneity is to add some extra heating in some parts of the greenhouse. In this case more energy will be used for a more homogeneous greenhouse climate.

## 6.3 Data analysis

The data analysis has also some limitations. The sensors which are used have all their own uncertainty in their measure which could be up to 0,4 K. With the calculation of the inhomogeneity the absolute temperature difference between the highest and lowest measured temperature is used. The accuracy of the sensors has therefore an effect on the inhomogeneity.

The measurement period for greenhouse 1 was a couple of months in the spring period. It would be better to analyse a longer period over a year including the winter. This will include more moments when heating is required and when critical climate moments occur.

Because there are a lot of factors which are correlated with each other (see correlation map, table 5.1) is difficult to find the factors which could be the cause for the climate inhomogeneity.

By the analysis of greenhouse 2 it was first difficult to get familiar with the dataset, because the data was from an existing dataset. Therefore is was not possible to go and see how the measurements are done and how the greenhouse looks like.

## 6.4 Further research

From the results of this study became clear that is not yet possible to fully answer the research question. Therefore here some suggestions for further research are given.

The most important issue that still needs to be answered is whether growers can lower their temperature setpoint or VD settings without having less production or damage to their plants. To answer this question, interviews with a large group of growers is needed. In which growers are asked about their margins on their setpoint and their willingness to change this margins if the climate inhomogeneity is less.

Next to this a comparison needs to be made with already existing plant research. Save climate conditions from the plant research could be compared with the setpoints the growers from the interviews used. The comparison could give an indication how much the setpoints could be changed. The plant researches which need to be consulted should include save climate conditions for different types of plants. For example how long can a certain plant handle certain cold or wet climate conditions without having any drawback of it.

Another point for further research is monitoring the energy use of greenhouses. The measures to increase homogeneity in greenhouses are clear. Therefore the energy use of a couple of greenhouses should be monitored before and after measures are taken. The comparison of before and after should give an indication to what extend the setpoints could be changed and what the energy saving potential in practice is of increasing the climate inhomogeneity.

Models can also be important in further research. With the use of models the effect on energy use of changed setpoints could be estimated. Such models already exist. With the use of different input parameters the energy use for different setpoints could be calculated and compared.

# 7 Conclusions

The aim of this research was to estimate the energy impact of climate inhomogeneity in greenhouses and to investigate which factors could be responsible climate inhomogeneity. The main research question was: What is the energy saving potential for increasing the climate homogeneity in greenhouses? In this conclusion this question will be answered with the use of the sub questions.

*Quantitative relation between inhomogeneity and energy use*
In the literature there was only one quantitative relation found between energy use and a change in temperature setpoint. The relation was 10% energy saving by reducing the temperature setpoint with 1 K for a greenhouse with tomato plants. A change in the allowance of the maximum relative humidity could also result in energy saving 40% saving by allowing 93% RV instead of 84% RV. From the interviews only one grower could show some energy use data over the years. But this energy reduction of 28 percent in 3 years, was not only achieved by increasing the homogeneity. From the interviews also became clear that the willingness to change setpoints by growers is low. The quantitative relation between inhomogeneity is not yet clear and further research on this subject is needed.

*Factors causing climate inhomogeneity*
The literature study and interviews has shown that there are static cold and wet places and dynamic cold and wet places. The static places are caused by infrastructural causes and the dynamic places are caused by natural forces. Infrastructural causes for inhomogeneity could be faults in design, heating design, ventilation screens and other appliances such as AHU's. The natural forces which cause climate inhomogeneity are: outside temperature, solar irradiance and wind. From the data analysis could be concluded that in a greenhouse which is air tight and well insulated the influence of outside factors is minimized.

*Measured climate inhomogeneity in the greenhouses*
Inhomogeneity shows a large difference between day and night. In greenhouse 1 the inhomogeneity during night times with closed screens was about 1,5 K. During daytime it was on average 2,8 K. In greenhouse 2 the average inhomogeneity was higher about 3K during the night. There was not a sudden change between day a night for the average inhomogeneity because the screens are not closed and opened at fixed times. But during the day the inhomogeneity was also higher up to more than 5 K. The difference between greenhouse 1 and 2 could be due to the different measurement periods or because of the different properties of the greenhouse.

*Relations between the factors and the inhomogeneity*
The correlations found in the analysis are not as strong as what was expected from the literature and interviews. During the night there is not found any strong relation between the factors and the inhomogeneity, there are only weak correlations. During the day the screens and windows are open and the outside temperature, sun and wind could influence the inside climate. This results in higher inhomogeneity during the day. The correlations which are found in greenhouse 2 are weaker than the correlations in greenhouse 1. But the correlations found in greenhouse 2 during night time are stronger, but still weak. It is not possible to point out one or two factors which are responsible for climate inhomogeneity. But clear is that if the influence of outside factors is minimized (well insulated and closed windows) the inhomogeneity is lower.

It is still unclear what the energy saving potential is if the climate homogeneity is increased, further research on this topic is needed. Growers will have to lower their heating temperatures and change VD settings to save energy. But growers will only do this when they are sure that the whole greenhouse stays within save climate margins, so there is no negative effect on production.

# 8 Acknowledgements

This study would not have been possible with the help and effort of the following people:
First I would like to thank Egon Janssen (TNO) for his supervision, help and motivation. Next I would like to thank Peter de Jong and Bas Knoll (TNO) for their daily supervision and technical assistance.
The help and cooperation of Andre Lankhaar and Ard Kerkhoven (Kwekerij Lankhaar) was necessary to preform measurements with wireless sensors in the greenhouse.
Thanks also go to Bas Visser (Wireless Value) and Rob Wientjes (Climeco) who shared contact details of growers who performed measurements with WSN. These growers are contacted for interviews and their cooperation was therefore also essential.
During my time at TNO I also participated in the technology cluster homogenous greenhouse climate. Therefore I would like to thank all the participants for sharing their knowledge and information.
Finally my thanks goes to Evert Nieuwlaar (Utrecht University), who supervised this master thesis project on behalf of the university.

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# Appendix I: Questionnaire growers

In Dutch

**Kasgegevens**
Bedrijfsnaam:
Naam:
Datum:
Gewas:
Kasgrootte: formaat: m x m
Hoogte:
Bouwjaar:

**Deel 1: Periode voor de metingen**

1. Wat merkte u van klimaatverschillen in uw kas, voor de metingen?

2. Leverde dit problemen op voor de productie? Zo ja, welke?
   - Natslaan van het gewas
   - Verhoogd schimmelrisico
   - Groeiachterstand
   - Achterstand in productie
   - Verminderde productie
   - Verminderde kwaliteit
   - Meer uitval door plantschade
   - Etc ……

3. Welke maatregelen nam u voorheen naar aanleiding van deze klimaatverschillen? Wat waren hiervan de voor- en nadelen?

4. Wat was de reden om metingen te gaan doen? Welke verwachtingen had u?

**Deel 2: Tijdens de metingen**

5. Hoe groot waren de gemeten temperatuur verschillen in temperatuur en RV?

7. Waar in de kas traden de gemeten klimaatverschillen op?

6. Kunt u aangeven in hoeverre de klimaatverschillen samenhangen met
- Het seizoen
- De weersomstandigheden
- Het etmaalritme (dag/nacht)
- Instellingen van klimaatsystemen (verwarming, luchting, scherming, e.d.)

9. Welke oorzaken zijn er door de metingen aan het licht gekomen?

10. Denkt u dat er nog meer oorzaken zijn voor klimaat verschillen? Zo ja, welke?

**Deel 3: De periode na de metingen**

11. Welke maatregelen zijn er genomen?
- Schermen standen
- Raamstanden/ventilatie
- Extra meetboxen/ andere locatie
- Klimaatregeling (standen/tijden)
- Verwarmingsstrategie/temperatuur
- etc….

12. Hebben deze maatregelen effect gehad? Kijkend naar inhomogeniteit, energiegebruik, productie en ziektedruk?

13. Zijn er gegevens beschikbaar die een verandering in het energiegebruik laten zien?

14. Voldeden de metingen aan uw verwachtingen? Wat blijft er te wensen over / wilt u nog verder verbeteren aan klimaatverschillen?

# Appendix II: Interview answers

| Gewas | Paprika | Gerbera | Orchideeen | Trostomaten (totaal 5 locaties, 35 ha waarvan de helft belicht |
|---|---|---|---|---|
| Kasgrootte (ha) | 2*16 ha | 2,3 ha | 2*3 ha | 5 ha |
| Formaat (mxm) | 185*304 275*400 | 120*190 | 100*130 | 200*250 |
| Hoogte nok/goot (m) | 6 m goot<br>7,5m nok | 3 m goot | 5,8 goot | 6 m goot |
| Bouwjaar | 2004, 2007 | 1989/90 | 2007 | 2009 |
| Klimaatverschillen merkbaar? | Niet heel veel, goed geinvesteerd bij bouw van de kas | Merkte niet direct iets<br>-Energieverbruik was erg hoog | Langs betonpaden aan zijkanten<br>noord/oost kant koud<br>zuid kant warm | Nvt. Meteen na de bouw gaan meten vanuit WUR. Daarna zelf meetset aangeschaft. |
| Problemen met productie? | Geen problemen met productie | Geen problemen met productie<br>-Veel verschillende rassen, dus lastig vergelijken | Bladschade | nvt |
| Maatregelen hierop | Maatregelen bij de bouw:<br>-Energiedoek<br>-2 schermen met daartussen schot/foli<br>-Nokschot om de 50 m | Wel ventilatoren voor luchtstroming | -Temperatuur metingen<br>-ventilatoren | Bij bouw(HNT): Schermen, ontvochtigers, ventilatoren<br>-goed geisoleerde gevels (stegdoppelplaten)<br>-overdruk in de winter |
| Reden voor meetingen met verwachtingen | Nieuwe kas doormeten<br>Goed beeld krijgen wat er 's nachts gebeurd<br>mulittoepasbaar, ook in hal | Wireless Value uit Emmen wilde bedrijf in de regio om sensoren in praktijk te testen. | -Groenlabel<br>-Kijken waar precies warm en koud<br>-4/5 jaar geleden gedaan | -Inzicht krijen in HNT systeem<br>-Gelijk mogelijk klimaat om energie te besparen |
| Hoe groot verschillen? | 1 C, dus dat is klein | Homogeniteit was 60% in range van +- 0,75C | 3C gemiddeld en 5C peik | Goede homogeniteit, verschillen binnen de 1C |
| Waar in de kas? | 5-10 m vanuit gevel door koudeval van boven het doek (bleek niet uit meetingen) | Vooral links achterin de kas warmer(afd 5) | Noorden gevel koud.<br>In midden warm. | ietsjes kouder aan de gevel |
| Samenhang met omstandingheden | Extra zichtbaar bij extreme kou in de winter | -Grotere verschillen bij heel koud en heel warm weer<br>-De ene plek wordt soms meer verwarmd dan de andere | Er is relatie tussen windsnelheid en windrichting<br>Grotere verschillen in de nacht. | Windrichting, warmte trekt naar wind hoek<br>bij koude buitenT |
| Gevonden oorzaken | -Koude buitenT<br>-Slechte configuratie ventilatoren | -Technishce mankementen aan verwarmingssysteem<br>-Schermdoek niet kieren | -Gevel verwarming niet apart<br>-aanvoer en retour zorgde voor warme zone in midden | Siloruimte aan kas vast, die hoek was iets kouder planten groeide daar minder. |
| Meer oorzaken? | -Verwarmingsysteem, warmteverlies over de lengte | Windrichting | - | - |
| Welke maatregelen genomen? | -configuratie ventilatoren veranderen<br>-met de hand bedienbare kraantjes op buizen<br>(Beide in klein kasje de twee grote kassen waren al goed) | -T groeibuis verlagen<br>-Kleppen goed afgesteld<br>-Schermdoek als 1 geheel laten regelen<br>-Ondernet gelijkmatig geregeld<br>-Zelf(handmatig) buis T regelen(op lage T) op basis van weer voorspellingen en sensoren<br>-Scherm vaker 100% sluiten<br>-Grotere dT tussen lucht boven het doek en kaslucht creeeren. | -Gevel verwarming losgekoppeld<br>-Aanvoer en retour geisoleerd in het midden van de kas<br>-nokschotten om de 33m<br>-Doeken los gekoppeld om te ventileren<br>-Ramen oostzijde los gekoppeld<br>-Noord en oost gevel geisoleerd | (Geldt vooral vooral voor andere kas niet voor deze)<br>-Extra isoleren<br>-Buis erbij leggen<br>-Raam lekkage dichten<br>-Kleine gaatjes dichten maken, voor overdruk<br>-Isoleren aanvoer leiding met aluminum verf<br>-Deksels op luchtslagen bij koud<br>-Nokschotten om de 30 m |
| Effect maatregelen? | Homgeniteit: toegenomen, maar arbeidsintensief door kraantjes<br>-Werkt ook goed in de hal | Homgeniteit: nu 90% in de nacht en 85% overdag<br>-Energieverbruik zie tabellen | Homogeniteit: verbeterd<br>Energieverbruik: verwachting is positief effect<br>Ziekte: Zo goed als over | Homogeniteit: Verbeterd, maar kan meer.<br>Energiegebruik: positief effect |
| Data verandering energieverbruik | Geen data<br>-De meetbox te laten corrigeren door de sensoren kan een oplossing bieden<br>-Er zou mogelijk scherper gestuurd kunnen worden | Zie grafrieken | geen data | Niet beschikbaar |
| Voldeden de meetingen aan verwachtingen? Nog meer verbeteren? | Meetingen voldeden aan verwachtingen (dus bij de bouw was er goed over na gedacht)<br>-Meetingen in de vrucht<br>-Meer meten zoals CO2/luchtstorming met de sensoren | Meer dan aan verwachtingen voldaan<br>-T zo rustig mogelijk regelen, lagere T verschillen in je buizen.<br>-Sensor data koppellen aan modellen voor groei/ziekte en dat weer aan klimaatpc of instellingen voor klimaatpc<br>-Transportnet op lage T laten rondlopen<br>-Meer op setpoint gaan sturen marges verkleinen<br>-Bij mooie dagen niet meer op VD laten regelen. Vochtige perioden in nacht worden overdag gecompenseerd | Ja, geeft goed beeld<br>Vaker meten zou goed zijn<br>-Verwarmings T kan omlaag meer de grens opzoeken | Ja/nee, sensoren hebben niet altijd bereik. Daarnaast invloed van de zoninstraling.<br>-Het is makkelijker om te sturen op een gelijker klimaat. |

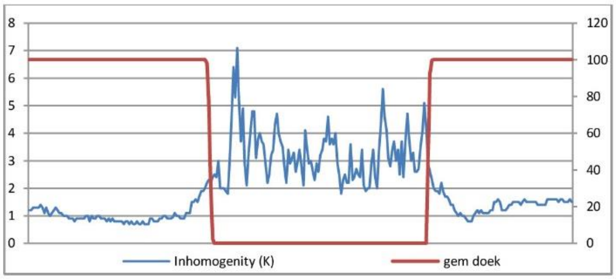
| Gewas | Tomaat | Gerbera | Orchideeen | Tomaat/komkommer |
|---|---|---|---|---|
| Kasgrootte (ha) | 2,5 ha | 3,2 ha | 3 ha | 2 ha |
| Formaat (mxm) | 192*133 | 204*152 | 130*232 | 130*150 |
| Hoogte nok/goot (m) | 5 m goot | 6 m goot | 4 m goot | 6 m goot |
| Bouwjaar | 2003 | 2013 | 1991 1996 2001 | 2012 |
| Klimaatverschillen merkbaar? | Kou aan de gevel<br>In winter vast foli onder het scherm. | Niks | | Was voelbaar, meer dan 6 graden |
| Problemen met productie? | Geen problemen | Geen problemen | Zou kunnen, maar geen directe problemen. De hele teelt komt langs zelfde plaatsen omdat ze containters staan. | Botrytis |
| Maatregelen hierop | Was al gelijk klimaat | Bij bouw(HNT):<br>nokschotten,ventilatoren, LBK's | -Ventilatoren<br>-Veel kleine buizen op lage T<br>- 3 schermen | -starten met meten |
| Reden voor meetingen met verwachtingen | Benaderd door Climeco<br>-Rare dingen gezien | -Plekje over in project Tgelijkmatigheid<br>-Interessant om te kijken hoe HNT is geregeld<br>-Check om het HNT homogener | -Het klimaat moet beter<br>- inzicht krijgen | -Inzicht krijgen in klimaatverschillen |
| Hoe groot verschillen? | Meer dan 3 C | Bij kieren van het scherm en koude buitentemperatuur 5-6C | Gemiddeld, viel niet tegen | meer dan 6 graden<br>gemiddeld 3-4C |
| Waar in de kas? | -Warm bij het beton pad in het zuiden<br>-Koud in westen te grenst aan verwerkingsruimte | Koud aan de kopgevels en warm rond middenpad | hoeken en bij de deuren | langs kopgevel / middenpad wisselend |
| Samenhang met omstandingheden | Warmte trekt naar wind hoek | Groter naar mate groter verschil met buitenT<br>-Overdag minder omdat schermen open zijn | | Bij kieren grotere verschillen<br>- Zoninvloed<br>- instelling LBK |
| Gevonden oorzaken | -Betonpad warmt op door de zon<br>-Aanvoer T geververwarming snel opgevoerd | -Luchtstroming tussen schermen door, door het afschot<br>-Luchting zorgt dat overdruk verdwijnt en dat er hoger dT ontstaat<br>-Afwijking in de sensoren van meetbox | _Verkeerde configuratie ventilatoren<br>- Kieren schermen | - Koudeval door scherm<br>- Zon<br>- LBK's aan de buitenkant bliezen warmere lucht |
| Meer oorzaken? | Maximum buis is niet goed -> zorgt voor ongelijkheid doordat er te snel verwarmd wordt. | Wind, Door overdruk is dat effect minder. Er is dan minder invloed van buitenomstandigheden | -Veel wind, kan opgelost worden met overdruk | Luchtstroming |
| Welke maatregelen genomen? | -Groeibuis ingeschakeld op 40C.<br>-Foli boven pad weg<br>-Gevelverwarming getemperd<br>-Aanvoerbuis met isolatieverf | -Het kieren van de schermen minimaliseren<br>-Minimaliseren van de luchting<br>-VD sturing van 2,5 naar 1,7 g/m3<br>-Nieuwe meetboxen, hortimax droge natte bol | -Schermen meer dicht en beter sturen.<br>-Ventilatoren veranderd<br>-Invloed naast gelegen koude of warme afdelingen<br>-Assimatlieverlichting<br>-Warmte naar hoogste punt | -Verwarmings buis LBK eerst langst middelste<br>-Hogere T lucht door LBK laten blazen om koudeval aan de gevel te voorkomen<br>-Een buis geisoleerd op te warme plekken |
| Effect maatregelen? | Homogeniteit: Verbeterd<br>Energieverbruik: Positief effect verondersteld | homogeniteit: groenlabel dT binnen 1,5C<br>energiegebruik: effect verondersteld | Homogeniteit verbeterd. | Homogeniteit: Stuk verbeterd kleinere verschillen<br>Energiegebruik: kan omlaag per kg product. Evt ook marges verkleinen<br>Ziektedruk: minder |
| Data verandering energieverbruik | Geen data | Lastig andere winter, maar effect verondersteld | - | - |
| Voldeden de meetingen aan verwachtingen? Nog meer verbeteren? | Ja.<br>Wellicht nokschotten zetten (in andere kas al wel om 33 m, dat werkte goed) | - Resultaten waren onverwacht,<br>-capaciteit van LBK's moet nog omhoog naar 6 m3/m2/h<br>-Je teelt inprincipe op je slechtste waarde, dus hoe homogener hoe meer de grenzen opgezocht kunnen worden | -Metingen geven goed inzicht<br>- Metingen zouden goedkoper moeten<br>- Niet in 1 keer goed, kleine veranderingen kunnen groot effect hebben<br>- bij homogenerklimaat kunnen marges verkleint worden | T metingen deden het goed,. RV geeft te hoog aan.<br>- Het is continue verbeterproces wellicht in de toekomst nokschotten |

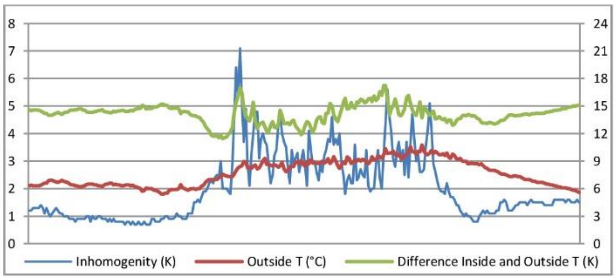
# Appendix II: Comparison extreme conditions

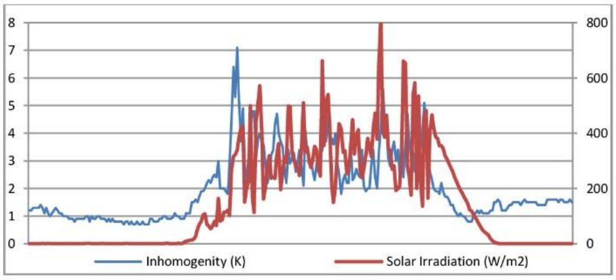
On the left side there is a day and on the right side there is another day, which are different on temperature, solar radiation or wind speed. Those days are compared in five graphs to see the effect on inhomogeneity: screen, outside temperature/difference inside and outside, solar irradiance, wind speed and ventilation.

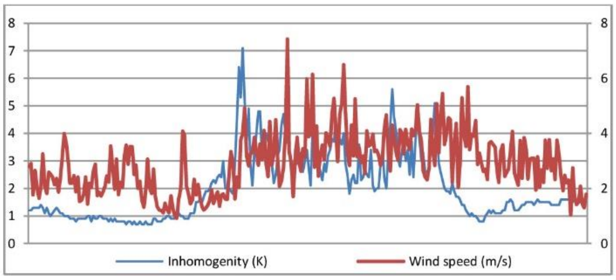
### Temperature

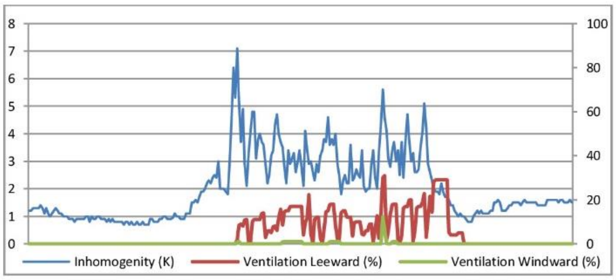
**15-4-2014: Cold - average 7,7°C**



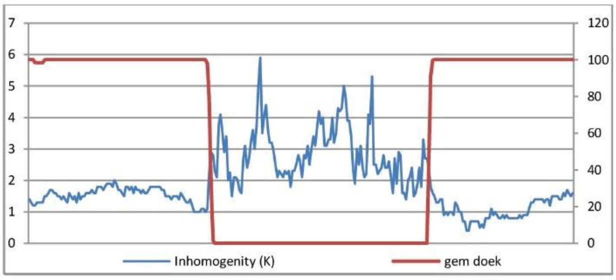



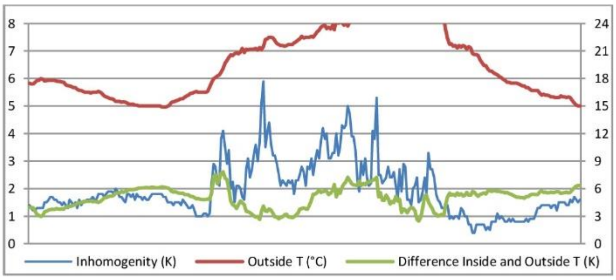



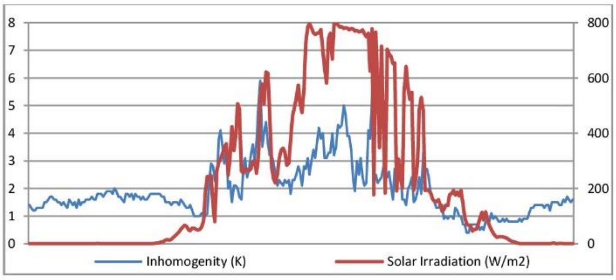



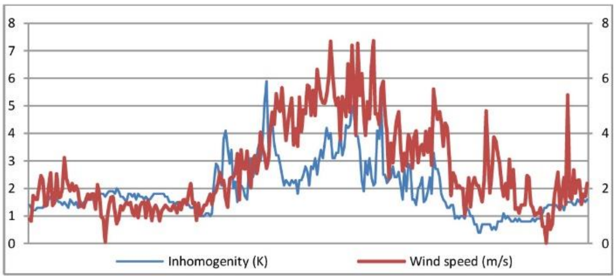



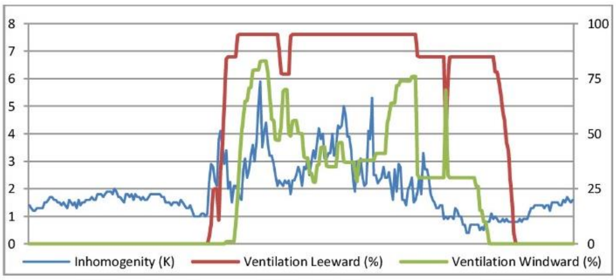

**20-5-2014: Hot - average 19,6°C**



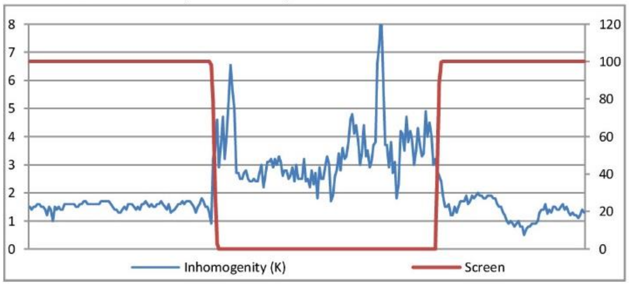



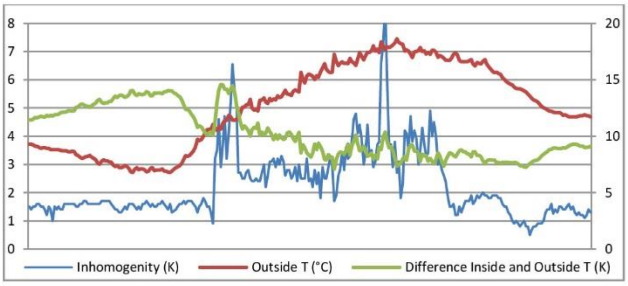



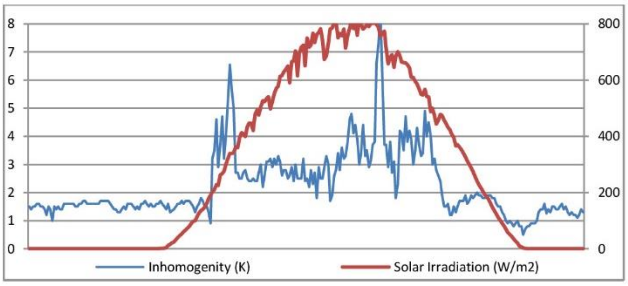



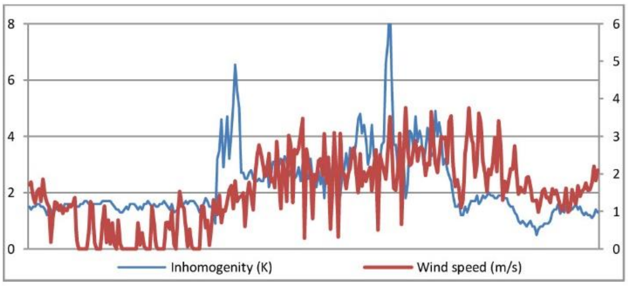
## Solar irradiation

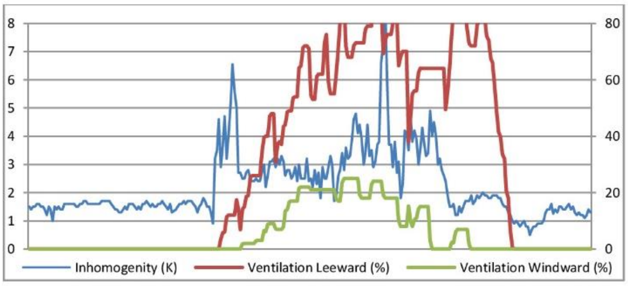
### 16-5-2014: sunny - average 290 W/m2



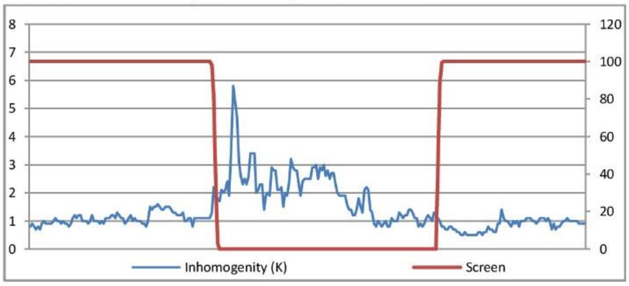



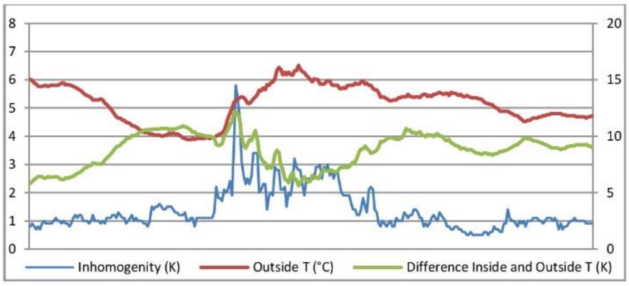



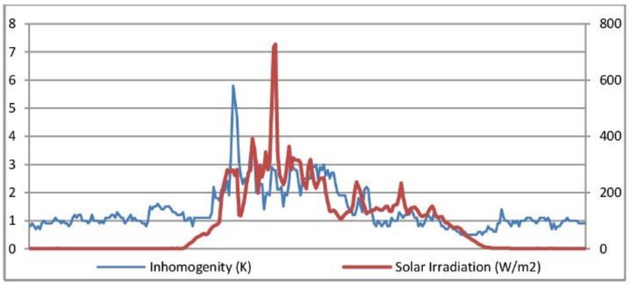



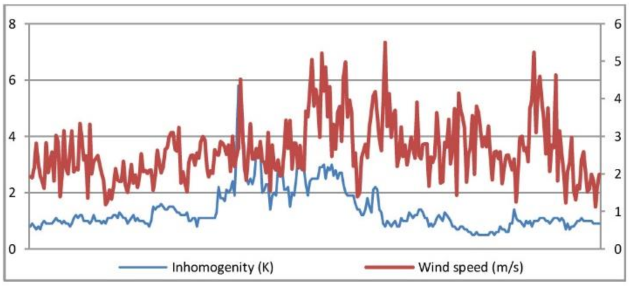



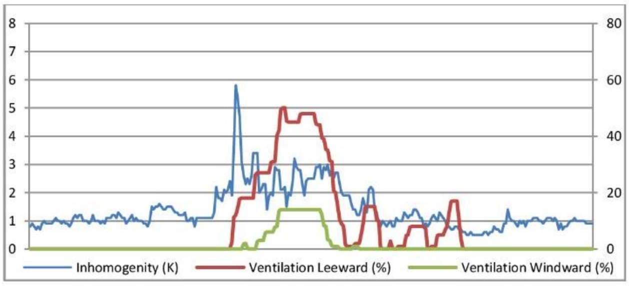

### 21-4-2014: cloudy – average 92 W/m2



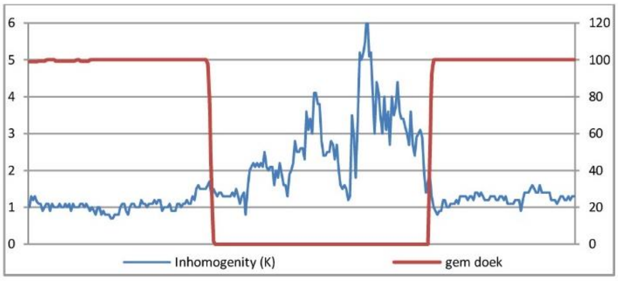



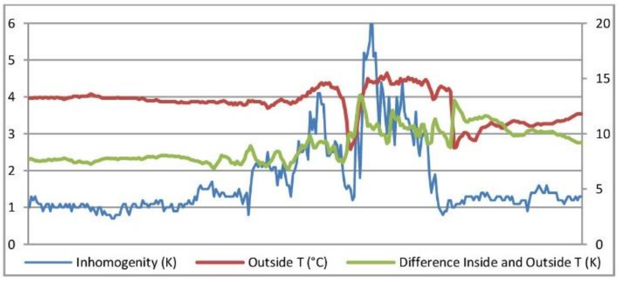



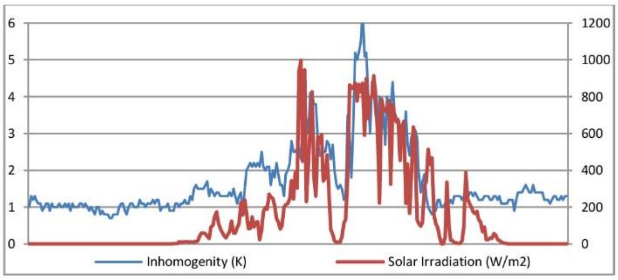



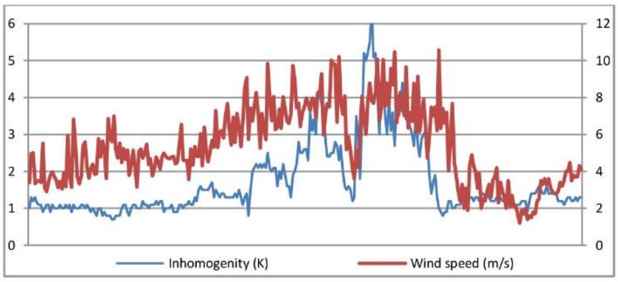
## Wind

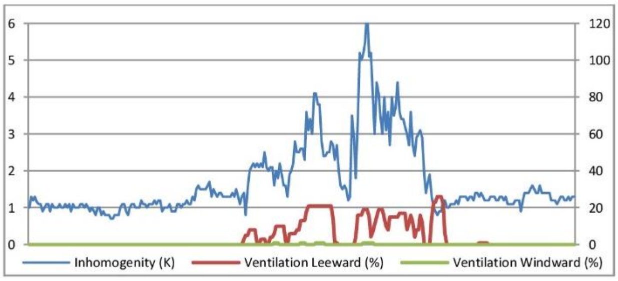
### 9-5-2014: Windy - average 5,4 m/s




### 23-4-2014: little wind - average 0,9 m/s