
MSc thesis Biosystems Engineering

Storage of arable products;

Optimal climate control with focus on renewable energy

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Foreword

The thesis report in front of you is the result of my personal interests. My name is Lennaert Haanstra and I am a Master of Science student Biosystems Engineering at the Wageningen University and Research Centre. After completing my Bachelor at the same study in June 2013, I've started my Master program in September of that same year. Before I came to study in Wageningen, I lived in the north of the province Flevoland. In this area a lot of arable farms are located. At home we have an arable farm as well and my plan is to continue this farm after my graduation at Wageningen University and Research Centre.

The basis for this thesis is my personal interest for optimization of processes on the farm itself. The reason for this is partly to achieve a higher durability of the agricultural sector but also the improvement of the financial result of the farm plays a role. In this case study it is chosen to optimize the instantaneous use of self-produced energy on the farm. Therefore the economic efficiency of the system increases and the total financial result of the farm. I hope that I can achieve this and contribute to a more durable and financial more healthy agricultural sector in this way.

This thesis would not have been a success without my supervisor. Therefore I would like to thank him for his efforts and inexhaustible patience with me.

dr.ir. L.G. (Gerard) van Willigenburg

Furthermore I would like to thank Tolsma Techniek Emmeloord b.v. and Albert Hoorn in person for their cooperation and information. This thesis would not have been possible without their support.

Summary

Storage of arable products has been very important from the beginning of arable farming. A storage is necessary due to a different moment of consumption and production. Major improvements have been achieved in storing techniques since the beginning of agricultural storages. Where the old storage facilities were just a hole underneath the ground, the most modern storage facilities are fully automated with computers and are equipped with artificial cooling and ventilating systems to maintain an optimal constant temperature. The down side of this is that the storage equipment needs a lot of energy to reach this temperature and that is not ideal in moments like these when the world is very critical about large energy consumers.

Farmers are investing in extracurricular activities to spread the financial risks of their farm. Over the last years it has been very promising to invest in the production of energy by using windmills and solar collector systems due to positive legislation and governmental support. The economic benefits of the electricity production are a welcome addition to the financial result of the farm. But the biggest part of the economics of energy on the farm has to do with the storage facilities for the arable products. The financial result of these installations isn't optimal yet due to different prices for energy delivering to the grid and energy consuming from the grid. The financial most interesting thing to do is to use energy produced on the farm instantaneously as much as possible. Thereby the energy exchange with the grid will be brought back to a minimum and the profitability of the farm increases.

The problem however is that storage facilities need energy at moments where there is no or not enough solar irradiation to fully satisfy this demand. The computer of the storage facilities however does not take into account the energy produced by the solar collectors in its decision making. In this way there isn't any cooperation between both systems. The target of this thesis is to couple both systems to each other so that the storage computer takes into account what the solar energy production is and makes decisions based on the solar energy as well as constraints on storage facility temperatures. The purpose of this is to cool or ventilate more often when solar energy is available so that on other moments, when no energy is available, no cooling or ventilation actions are necessary.

In this thesis a case farm has been used with a solar production installation of 91.000 watt peak. On the same farm three storage facilities are present for 450 boxes of seed potatoes, 850 tons of unions and 1290 boxes of carrots and celeriac. The farm will be simulated by models of every part of the farm implemented in Matlab. The control system which is already present will be implemented to calculate the financial result for the situation as it is now. The next step is to find a way to create a link between both systems so that the control system takes the solar energy production into account as well. To do this information is gathered about the energy use of all the installed equipment. Based on this information, the computer will calculate which equipment may be activated using the currently available solar power. In this way the instantaneous use of energy will be increased and the energy and economic efficiency with it. The target of this research is to come up with a control scheme capable of doing this and to calculate the improved efficiencies.

The outcome of this research shows that the financial benefit is around €2200 per year for the case farm after the two systems are coupled. The computation is made assuming average weather conditions and uses simulation models that only approximately describe reality. Considering the size of the improvement it can be said that the financial result of the farm will increase when both systems are coupled. Advantage of this link is that only software has to be adjusted and so the investment costs are low. Therefore this innovation could be very promising. Another result is that the energy demand from outside the farm will be lower than before so the farm becomes more durable as well.

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1 Introduction

Since the beginning of arable farming, storage was very important because moments of harvesting do not match moments of consumption. Storage is required to have food available all over the year instead of only during small periods of time. Times have changed and now the consumer wishes not just to have food all over the year but also to have every product available year round and with the same high quality. This wish demands a high quality storage keeping product quality at the original level like it was harvested yesterday.

Since the beginning of storing food, lots of improvements have been realized. From storing food underneath the ground towards a high-tech storing facility building with ventilation systems, measuring devices and artificial coolers. All this equipment is controlled by a computer that uses the measurement data to make sure the product stays at the same quality as it was harvested. Storage facilities with this equipment can be seen as the most modern storage facilities at this moment. Only disadvantage of all these equipment is that a large quantity of energy is needed to feed all this equipment.

At this moment a different trend can be seen at farms; energy production. The production of energy at farms has been growing exponentially during the last few years. Main reasons for this are the raising energy costs, the decreasing prices for energy production systems, larger availability of energy production systems and the governmental support for producing renewable energy. The most advantageous is to use the produced electric energy instantaneously. This is because the price for selling energy now is less than for buying it back at a later moment. This is partly due to energy tax that has to be paid over every kilowatt-hour extracted from the grid.

This thesis focusses on both these trends on arable farms. This research is aims to optimize profit obtained from energy production by increasing the instantaneous use of it thus minimizing energy exchange with the electricity grid. The storage facilities will be used as variable consumers of energy to reach this target. In summary all this is captured by the following major research question: “In which way and to what extend can the production of electric energy by solar collectors contribute to profit obtained from storage facilities?”

This major question will be supported by the following sub questions:

- What are ideal climate conditions for storage of different crops?
- Can a control system be created that raises profit by creating a link between both systems?
- What are the economic benefits and costs of using solar collector power instantaneously?

First a literature research will be performed to get more information about the background of storing agricultural products and about energy production on farms. Next a case farm which will be used as an example for this thesis. Subsequently a Matlab model will be made to simulate the case farm. Next, this model will be adjusted to simulated the link between the energy production system and the storage systems that is created. Finally the economic benefits of this link will be evaluated.

2 Literature & background

2.1 History of arable farming in northern Europe

The human as we know now appeared around 40.000 years ago in northern Europe according to Ziehr (1984). In the ice Age people were hunters and 90% of their food consisted out of animal protein. The other 10% consisted out of berries, spices and roots. Small technical improvements of tools like carved stones made life easier but in the origin, life wasn't changing radically.

During the Mesolithic people survived the ice Age but the population in the affected areas was decreased to 10 or 20%. A family just needed a few hours to feed their selves properly. The large herds had become smaller due to the ice age but people had the possibility to fish as well. Also the availability of other foods had increased like bird eggs and plants with fruits. However people lived on the same cultural level as they did in the Stone Age. There was room for everyone because the population density was very low. Every tribe was able to find temporary places to stay. As long as the hunter came back with enough animals and the women were able to find enough fruits and plants, the tribe was able to stay at the same place for a longer time. Also the climate played an important role in this.

After this period the way people lived changes rapidly. The oldest known villages were built between the Negev and the Euphrates in the Middle East around 14.000 BC. These permanent communities may have consisted out of some dozens of round houses which were partly build underground. The large amount of millstones and jacks which were found inside the houses point out the importance of grain harvest. From around 12.000 BC it can be seen that some agriculture and livestock developed. The most important changes in this area occurred between 10.000 and 9.500 BC where the first agricultural experiments have been done in larger and densely populated villages. People were no longer satisfied with the harvesting and storage of food. They started to focus on the reproductive process of the eatable plants on prepared soil with special selected seeds. This can be seen as a precursor of breeding.

Larger mutual dependence and cooperation arose due to which welfare and populations increased. This inevitable demanded a higher production of food which led to trade contracts, domination, services and subordination. Because the plant breeding was going well, farmers created a surplus of food. This surplus made it possible to do barter. In this way a farmer could exchange his surplus of wheat against livestock, animal skins, gems and others. Besides, some members of the agricultural communities could start doing other jobs like priest, soldier, artist craftsman or trader. From these changes, modern civilisation arose.

A more intensive arable farming led to a fast increase in population Ziehr (1984). The north of Syria and along the Mediterranean seacoast were the first to show the spreading of villages and a systematic search for soils which were best suitable for agriculture. In Europe the first agriculture and livestock communities arose around 8.000 BC. This was the start of an impressive expansion of the agricultural communities in Europe. Because communities were no longer travelling in their search for food and in an attempt to escape from the colder seasons which provide less food, the availability of proper storage of food became more important.

2.2 Modern arable farming northern Europe

2.2.1 Developments

Over the last decades, urbanisation has gone incredibly fast. People are now living in large cities were farmers on the countryside are producing food and supply cities. Farming techniques have been improved and the amount of harvested food is a record almost every year while farmers are allowed to use fewer inputs like nutrients on their farms. This has been one of the most important developments in the last decades. Another important development is scaling. Farms are getting bigger; this has to do with a reduction in production costs and in the amount of people who want to be a farmer. The next important development is due to technological development. More processes on the farm are mechanised and automated. This to improve working circumstances of the farmer and to make the scaling possible as well. The last important development concerns increase or start of secondary activities. Production of food is no longer the only way for farmers to earn their money. Some contribute to recreation or home sales while others produce something different than food, like energy. According to Hiethaar and Pierik (2004) almost 5400 farmers sold their products directly to consumers in 2003. This is nearly 6%. This can also be seen as a secondary activity.

2.2.2 Storage

Nowadays storage of food is still an important issue. Storage is necessary because harvest and consumption are not synchronised and the consumer wants a continuous availability and quality of food throughout the year. This initiates development and improvement of storage facilities. Modern storage facilities make use of artificial cooling using only natural cooling liquids and are monitoring crops so that product quality stays optimal and the loss in weight be reduced to a minimum, according to Tolsma Techniek (2014). Although current storage systems use less energy, the demand for electric energy is still large. Open farming used 507 million kilowatt hour, or 1.8 PJ, in total in 2011 according to Statline (2013). This energy demand has partly been used for processing on the farm but most of all for drying, cooling and storage of products according to Rougoor et al (2013). 33 PJ of electric energy has been used in the Netherlands in total in the same year according to Statline (2014). This means that 5.5% of the total energy demand in the Netherlands has been used for open farming.

2.3 Energy production on the farm

There were almost twelve thousand agricultural companies in total which also had activities outside the agricultural sector in 2007. From this other activities more than one-third was active in energy production, almost four thousand companies according to Terbijhe et al. (2009). To use rest streams better on the farm and to compensate for their use of electric energy, a lot of farmers are doing secondary activities on their farms by producing electric energy. Several options are available in the way of producing electric energy.

2.3.1 Windmills

In the Netherlands a lot of farmers are owner of a windmill. In 2003 around 460 farmers had a windmill at their farm according to Hiethaar and Pierik (2004). This slightly increased till 474 in 2007 according to Terbijhe et al. (2009). According to Oltmer et al. (2009) it seems that especially young farmers are (partly) owner of a windmill. Almost 75% of the agricultural owners is younger than 50. It seems that younger entrepreneurs prefer long term planning and starting earlier on wind energy. Although around 35% of the wind turbines in the Netherlands are owned by farmers, the production stays behind. Around 30% of the total produced wind energy is produced by agricultural

entrepreneurs because they build smaller turbines than the average windmill. An average windmill has a capacity of 1 MW and an agricultural windmill of 0.75 MW. The production of agricultural wind energy is around 1.2% of the total produced electric energy in the Netherlands. The largest part of this produced energy is sent to the grid. According to Oltmer et al. (2009) wind energy in the Netherlands saves 2.077 kilotons of CO₂-emission and agricultural wind energy saves 635 kilotons of CO₂-emission.

On the financial side, an average windmill will earn an income of 40.000 euro. Since most agricultural windmills are smaller than the average one, for agricultural entrepreneurs this income is around 20.000 till 30.000 according to Hiethaar and Pierik (2004).

2.3.2 Solar collectors

Installation of solar collectors has increased rapidly over the past few years. In 2010 around 25 megawatt was installed, in 2011 it was already 60 and in 2012 220 megawatt is newly installed according to Segers and Wilmer (2013). At the end of 2012 a total capacity of 365 megawatt was installed of which 220 megawatt was placed that same year.

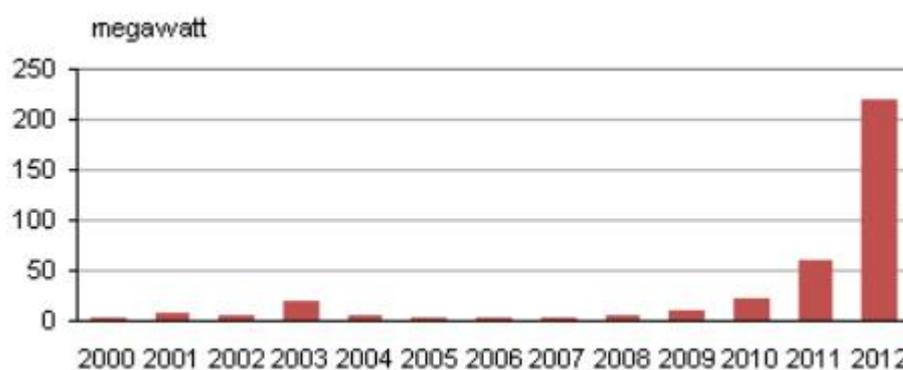


Figure 1 New placed power solar energy per year - *Segers and Wilmer (2013)*

Figure 1 shows the fast increase of solar collectors. From the 365 megawatt about 70% was installed at households. The agricultural share was 40 megawatt which is more than 10%.

This development also triggered institutions to support the installation of new solar installations. *LTO*, the interest group for the agricultural sector, started a trial for cooperative purchasing of solar collectors in 2011 to make them cheaper for her members. According to Rougoor et al. (2013) around 150 agricultural entrepreneurs bought solar energy systems with a total power of 5 megawatts. This was such a great success that in the second round already 460 participants bought a total power of 15 megawatts. With this total of 20 megawatts agriculture contributed directly to a better environment because these installations produce around 17 million kilowatt hours and save 10.000 tons of CO₂ emission. This shows the popularity amongst farmers to invest in solar energy. With a lot of subsidies the investment costs are kept low and profitability becomes higher. The best efficiency can be reached when the solar collectors are placed directed to the south, south-east or south-west under an angle of 35 degrees. It is also most effective when the electric energy is used instantaneously without sending it to the grid and pulling it back on a later moment according to Rougoor et al. (2013).

The impressive growth in the amount of solar collectors of the past few years has to do with several things. The first one is that they are subsidized in Netherlands which will give the owner less investment costs. Other arrangements have to do with tax benefits when they are installed for the owners which makes them more attractive. Another major influence on the fast growth is that solar collectors have become much cheaper in the past few years. Rougoor et al. (2013) report that the purchase of one Watt peak has decreased from 6 euro in 2007 till 2 euro in 2012.

Table 1 Electricity prices - CBS (2014)

Belastingen	Perioden	Elektriciteitsprijs		
		Verbruiksklassen huishoudens		Verbruiksklassen niet-huishoudens
		2,5 tot 5 MWh	2 000 tot 20 000 MWh	150 000 MWh en meer
Inclusief BTW en belastingen		euro per kWh		
	2007	0,175	0,105	0,075
	2008	0,178	0,108	0,084
	2009	0,193	0,119	0,083
	2012	0,187	0,102	0,071
	2013 1e kwartaal	0,198	0,103	0,081
	2013 2e kwartaal	0,184	0,105	0,082
	2013 3e kwartaal	0,187	0,103	0,079
	2013 4e kwartaal	0,203	0,100	0,077
	2013	0,192	0,103	0,080
	2014 1e kwartaal*	0,223	0,102	0,077

Surprisingly the fast growth in solar collectors has nothing to do with rising prices for electric energy because they are quite constant for the non-households as can be seen in table 1. So it seems that this is not a driving factor.

2.3.3 Digester

According to Rougoor et al. (2013) digesters were very promising a few years ago. However it has been seen that digesting is not profitable due to relative high costs for coproducts. The opinions about the future of this technique differ greatly. It may be that this technique is promising for the future but it may be surpassed as well. When this technique was considered quite promising a lot of installations have been built with governmental support. In total in the Netherlands 105 digester installations have been built with a total production of electrical power of 129 megawatts.

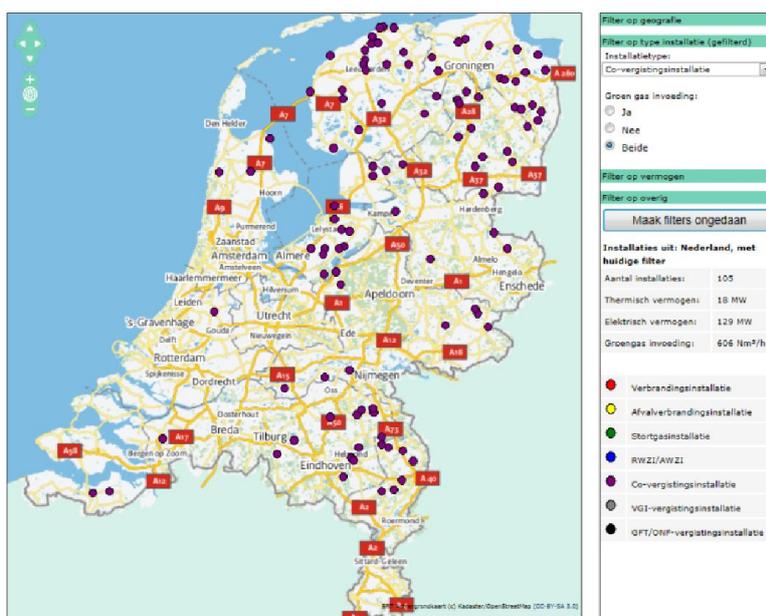


Figure 2 All digesters of the Netherlands - Agentschap NL

3 Thesis subject: improving profitability and energy efficiency of storage facilities including solar collectors

Case farm chosen as an example.

This thesis focusses on a farm located in Marknesse, the Netherlands. At this farm inter alia seed potatoes, unions, carrots and celeriac are produced and stored in a modern storage facility that includes artificial cooling. At the same location the farmer has installed solar collectors on the roofs of his barns. To improve profit obtained from the solar collectors a link between the storage systems and solar collectors will be developed in this thesis. In addition to this, energy control policies are developed.

As Rougoor et al. (2013) described, it is most profitable when the electric energy produced by the solar collectors is used instantaneously. To achieve this, a link between the solar collectors and the storage facility climate controllers is needed. Moreover associated control policies must be developed that exploit this link to achieve maximal instantaneous use of solar energy. This in turn may demand reconsidering rules of thumb determining climate conditions for storage. On the other hand the product quality may not suffer too much from this. With other words the profits on energy may never exceed the financial loss in quality. To realize this, information concerning the products to store, the storage system and the solar collectors will be used. In addition to this yearly weather conditions will also be used to determine what may be gained from our new developments as compared to the current situation.

3.1 Storage

There are several storage facilities on the case farm for specific crops cultivated on the farm. Some background information about how to store these products will be given first for every product. This will be directly followed by a description of the storage installation for these products on the case farm. A computer will be used to control all storage facilities.

3.1.1 Celeriac in storage background

Celeriac is a small cultivation in the Netherlands. The moment of harvest is a bit spread due to the different climates in the Netherlands. In the south-west the harvest starts already in the second half of October were in the north east the harvest starts a few weeks later around the second half of November. The celeriac can be stored in both a bulk storage as in a box storage. According to Buishand and Koomen (1977) the best temperature to store the celeriac is between 0 and 1 degree Celsius and with a relative humidity of around 95%.

For the CO₂ content inside the storage is 3% an upper bound. It may be that under these conditions discoloration of the inner tissue occur.

Koudecentraal is an institution which is part of Wageningen UR and TU Delft and is aimed to get more information about what happens with products stored in a cooling. When celeriac is stored in bulk, it has a density of 450 kilograms per cubic meter according to the handbook for the cooling technique written by Koudecentraal. The heat produced by the celeriac is at low storage temperatures 15 Watts per ton at 0 degrees Celsius and 19 Watts per ton already at 2 degrees Celsius. This information is from the handbook as well According to ASHRAE Research (2006) the specific heat of celeriac is equal to 3900 Joules per kilogram per kelvin.

3.1.2 Carrots in storage background

Carrots meant for long term storage are harvested in the second half of October and the first half of November. In most cases they are harvested directly in boxes and these boxes are stored in buildings equipped with artificial cooling. According to Nijssen (2005) the best way of storing the carrots is by keeping them directly after harvest for 12 till 24 hours between 12 and 15 degrees. This will have a strong positive effect on antibodies against fungus. After this short period it is recommended to cool down towards 0 till 1 degree Celsius. This temperature is optimal for the carrots to be stored for a long period of time. The storage temperature may fluctuate with a maximum between 0.6 and 0.8 degrees. Otherwise the temperature fluctuations become too big and the product quality will go down. The recommended relative humidity is between 80 and 95 to minimize dehydration.

The second important aspect in the storage according to Nijssen (2005) is the ventilation time. The carrots start to dehydrate if the ventilation time is too long. This will have weight loss as a result. Not more than 25 till 30 minutes on average should be ventilated per hour.

The last important aspect Nijssen mentions is the CO₂ content inside the storage. Even inside the storage carrots act like a living product, so they use reserve substances out of the carrot to sustain their life. In doing so the carrots are producing CO₂ and heat. Damage can occur if the CO₂ content of the air becomes too high. Nijssen says that visual damage arises when the CO₂ content is higher than 3%. However non visual damage can arise already at a lower content level. Therefore he mentions 1% CO₂ content as a maximum.

Other interesting and relevant information about the storage of carrots can be found in Sprenger (1983). When the carrots are harvested and have been put in boxes they behave as a small bulk storage in a single box. Carrots in bulk have a density of 440 kilogram per cubic meter. They also produce heat to sustain life. According to the handbook of Koudecentraal heat production of the carrots is at 0 degrees Celsius 9.7 Watts per ton and at 2 degrees Celsius already 22 Watts per ton. According to Sprenger (1983) the specific heat of the carrots is equal to 3920 Joules per kilogram per kelvin.

3.1.3 Carrot and celeriac storage facility specifications

In the case farm storage facilities carrots and celeriac are stored in boxes. Every box has dimensions 1.60 m x 1.20 m x 1.20 including pallet. The actual volume is equal to 1.60 m x 1.20 m x 1.05 m which is 2 cubic meters per box. These boxes will be stacked 6 high. In the storage facility there is room for 1290 boxes. From these 1290 boxes, 810 will be reserved for storage of carrots and 480 for storage of celeriac.

The carrot and celeriac storage facility is equipped with a propane/CO₂ refrigeration system. The first step in cooling is that CO₂ has to be compressed so that it becomes liquid by an electrical engine outside the storage facility. After compression, the CO₂ is transported under high pressure inside a so called evaporator inside the storage facility. This evaporator is placed against the roof inside the storage facility. In this evaporator, the pressure is released and the CO₂ becomes vapour again inside the evaporator. When the CO₂ vaporizes it takes a lot of energy from the ambient air. The ambient air will cool down as a result. This cooled air will be spread through the storage facility. After the vaporisation, the CO₂ goes back to be compressed again. The heat which is released when compressing CO₂ is released to the outside air. A picture of the evaporators can be seen in figure 1. In figure 2 a picture of the compressors can be seen. Figure 3 represents the system in a scheme.



Figure 2 Evaporators in the carrot storage



Figure 3 The compressors for compressing the CO₂ – *Tolsma Techniek Emmeloord b.v.*

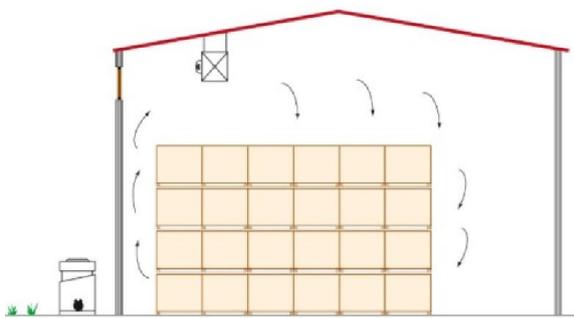


Figure 4 Schematic drawing of the carrot and celeriac storage – *Tolsma Techniek Emmeloord b.v.*

As can be seen from figure 3, three evaporators are installed inside the storage facility and they can be switched on individually. Each evaporator has a cooling capacity of 51.3 kW. The cooling capacity can be calculated from the electronic power consumption by dividing by 4. In other words, every electric kW can deliver 4 kW of cold. So when an evaporator is switched on, the energy consumption will be 12.83 kW. This cooling is needed to take away the warmth/energy produced by the carrots and celeriac. Also energy comes from outside by heat transfer through the walls and roofs. This energy has to be drained as well so that the optimal constant low temperature can be maintained.

3.1.4 Onions in storage background

Unions meant for the long term storage are harvested during September. First the last leaves are removed and after that the plants are lifted out of the ground and put on windrows. After a period of a few days on the field for drying, the unions are harvested and transported from the field for storage or immediately loaded on trucks and sold. They can be stored in a large bulk or in boxes. Drying begins after they have been put into the storage facility. For unions it is very important to dry them immediately after harvesting to avoid problems with the quality according to van den Broek (2003). When unions have been dried with forced ventilation and heaters, the temperature should be lowered very slowly; not more than one degree Celsius per week towards the final storage temperature.

According to van den Broek the most important thing is to keep the unions dry. The second thing is to keep the temperature as constant as possible. With a storage facility that is only cooled with outside air it is recommended to store the unions at minimal 6 degrees Celsius. When the storage is equipped

with artificial cooling, the onions can be stored best at 3 degrees Celsius, when stored for a longer period.

In the handbook written by Koudecentraal the heat production of onions in bulk storage is given. At 2 degrees Celsius the heat production is equal to 13 Watts per ton. The circulation rate for onions should be 30 times per hour according to this document. A circulation rate of 30 means that the air inside the storage should be refreshed 30 times per hour. This capacity is mainly needed during the drying period. The density of the onions is given; 550 kilograms per cubic meter in bulk storage. According to Sprenger (1988) the specific heat of onions equals 3780 Joules per kilogram per kelvin.

3.1.5 Onion storage facility specifications

In the case farm storage facility unions are stored in bulk. After the unions are harvested they are placed on a large pile. Underneath the pile, air ducts are present so that air can be transported through the unions. Fans will blow air with the right properties through the ducts and so through the unions. The right properties will be obtained by mixing outside air and inside air till. It is not necessary to ventilate 24 hours a day, ventilation is only needed to keep the unions on the right temperature. The storage dimensions for the unions are 29.78 m x 13.00 m x 4.25 m. Theoretically around 850 tons can be stored inside this storage facility.



Figure 5 The unions inside the storage with in the upper left the 2 evaporators



Figure 6 The air mixing chamber with in the front one of the eight fans

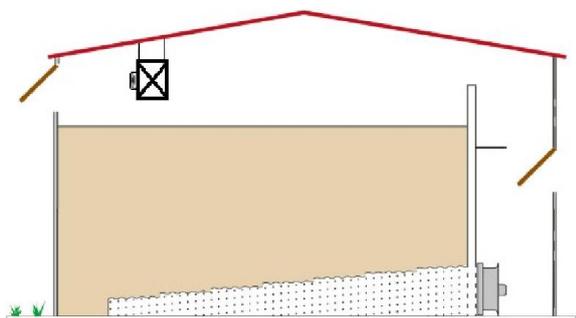


Figure 7 Union bulk storage air mix ventilation system schematic drawing - *Tolsma Techniek Emmeloord b.v.*

The union storage is equipped with two systems; a ventilation system mixing air and a refrigeration system. The ventilation system is represented by figure 8. It can be seen that on the total right, air is mixed. This air can be 100% inside air, 100% outside air and everything in between to get the right

conditions. A photograph of this air mixing chamber can be seen in figure 7. After mixing has been completed and air has the right temperature, it is blown by fans and air ducts through the union bulk. When the unions are ventilated with outside air, the air will go out of the storage again after it has gone through the unions. That can be seen on the upper left corner of figure 8 where a hatch is installed. Because of the circulation rate of 30 times per hour, the size of the storage and the amount of fans (8), every fan should have a capacity of 15150 cubic meter of air per hour. From information from Tolsma Techniek Emmeloord b.v. about the EC fans, the energy consumption of every fan is 2957 Watt when they are switched on. This system is only there to blow (mixed) air through the unions. This system does not cool the air itself. Therefore an artificial cooling system is installed inside the storage facility.

The cooling system is more or less equal to the refrigeration system of the carrot and celeriac storage facility but only smaller because unions require less cooling than carrots and celeriac. They can be stored at a higher temperature and are producing less warmth. Therefore the cooling system consists out of 2 evaporators only. The CO₂ compressors are the same as those used for carrot and celeriac storage, they are shared. Both the evaporators can be switched on individually and they consume 8650 Watt, when switched on. This means their cooling capacity is 34.6 kW. The cooling system is not used on its own. When the cooling system is activated, the air ventilation system should also be activated to blow the cooled air through the bulk storage.

3.1.6 Seed potatoes in storage background

Seed potatoes are potatoes that will be planted again next year to create more potatoes. The cultivation of it happens in several regions in the Netherlands. The purpose of this cultivation is to get potatoes of specific sizes to get a homogeneous product which is easy to plant. After the harvest in September, the potatoes will be dried and sorted on size. After the sorting they can be distributed or put back in storage to be distributed later. The Dutch seed potatoes are distributed to almost any country in the world.

According to the handbook written by Koudecentraal the seed potatoes produce 12 Watts heat per ton when they are stored at 5 degrees Celsius. In this same document also the density of the potatoes is given; 650 kilogram per cubic meter. The book of ASHRAE research (2006) gives information about the specific heat of potatoes, which is equal to 3670 Joules per kilogram per kelvin.

According to Bus (1996) the ideal temperature to store seed potatoes is 3-4 degrees Celsius. At this temperature the dormancy is optimal. However at these lower temperatures the life processes take more energy out of the potato then when they would have been stored at 5-7 degrees Celsius. This will mean that a larger loss of weight will arise because reserve substances will be used and converted into CO₂.

To reduce a larger loss of weight it is recommendable according to bus (1996) to keep the relative humidity inside the storage very close to 100% but without ever reaching it. Otherwise the potatoes will be dried by the passing air and lose their water content. A loss of water content means a loss in weight. In this way the potatoes will have a minimum loss of water towards the ambient air. The circulation rate in potatoes is 27 times per hour according to the handbook from Koudecentraal.

3.1.7 Seed potato storage facility specifications

When the potatoes are being harvested, they are immediately stored in boxes. The potatoes are still a bit humid when they are harvested and therefore they have to be dried. This can be done with forced air by ventilation ducts or by natural passing air. In this case the farmer has chosen for storing them a short period of time under a canopy so that the outside air will dry the potatoes. When they are dry, they are put inside the potato storage. This storage has a capacity of 450 boxes with a volume of 2 cubic meters. A representative drawing of the storage can be seen in figure 9.

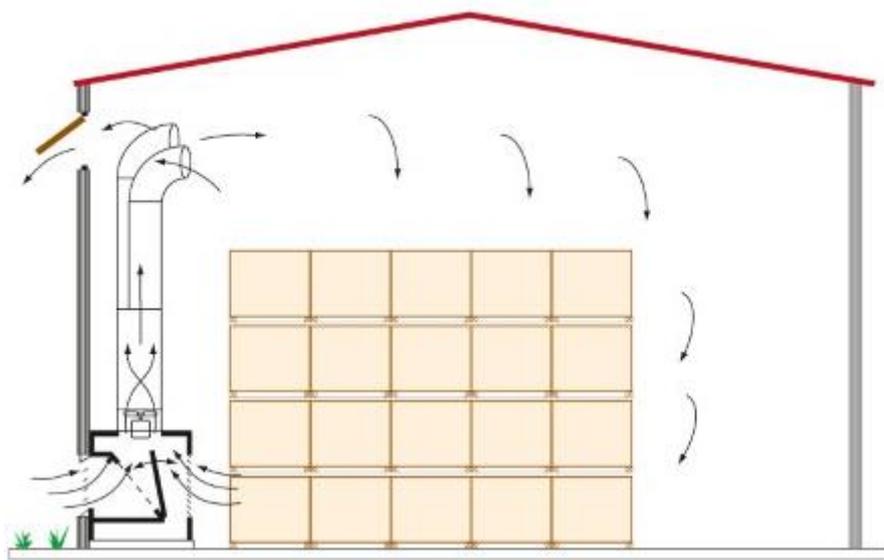


Figure 8 Seed potato storage schematic drawing – *Tolsma Techniek Emmeloord b.v.*

The seed potato storage is equipped with a so called air mixing unit of type QML-40. This unit has the possibility to mix outside and inside air. After the air has been mixed, the air is blown over the top of the storage boxes with potatoes. Because this air is cooler than the inside air, the cool air will go down and the potatoes will be cooled/ventilated. When this unit uses outside air, the air from the storage will be released by a hatch towards outside. It is also possible to cool the air by a refrigeration system like the one for carrot and onion storage. This takes place inside the air mixing unit. The circulation rate for potatoes is 27 times per hour. Because there are 2 fans in this system and the volume of the storage is 909 cubic meters of air, the fans must have a minimum ventilation capacity of around 25.000 cubic meters of air per hour. According to Tolsma Techniek Emmeloord b.v., the 2 installed fans have a capacity of 52.000 cubic meters of air per hour. So 26.000 cubic meters per fan per hour. When those fans are activated, they consume 1651 Watt. The artificial cooling capacity is 40 kW and therefore the energy consumption for cooling is 10 kW. Like the onion storage, fans should be activated to blow the cooled air through the storage facility.

3.2 Control System

Vision Control is the name of the computer that is controlling the climate in all storage facilities. The computer has a large number of settings some of which are directly presented to the farmer. These include desired temperatures, wishes for ventilation, like the maximum ventilation time, time boundaries for ventilation and the ventilation capacity. A lot of settings have been pre-programmed but can be manipulated as well.. Also there is a program called “wound healing” to be used directly

after harvest, for long term storage and for warming up the product just before leaving the storage facility.

Every storage has its own temperature measurement devices. This information is sent to the computer to control every storage facility. The computer will calculate if internal or external ventilation is needed and realize it. The same holds for the refrigeration system.

In pictures 10 till 12 the Vision Control can be seen for carrot and celeriac storage, union storage and seed potato storage.

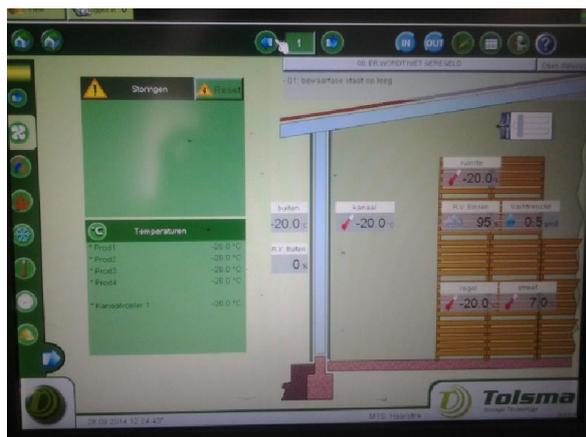


Figure 9 Carrot and Celeriac storage in the Vision Control

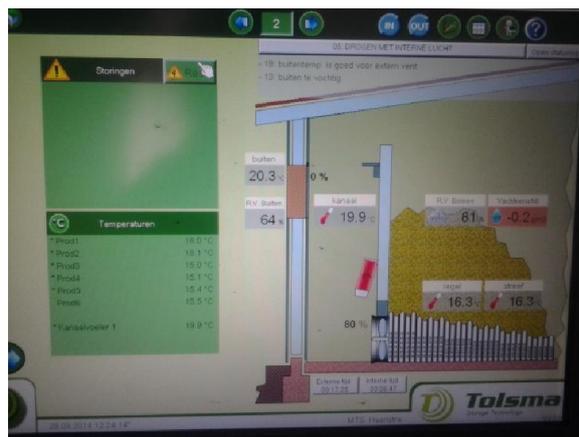


Figure 10 Union storage in the Vision Control

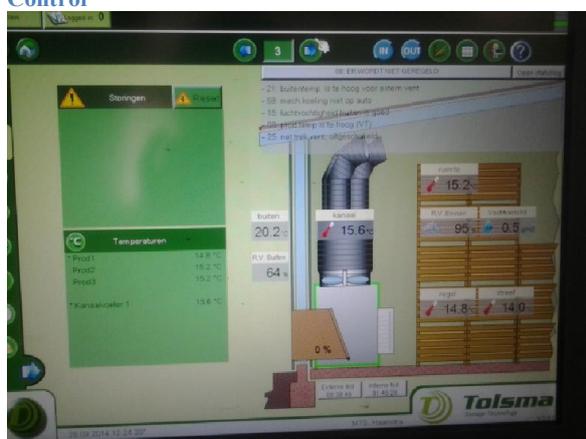


Figure 11 Seed potato storage in the Vision Control

3.3 Energy production

The energy production on this farm is realized by solar collector panels. There are a lot regulations for solar collector panels and therefore first some background will be given. Next the situation on the case farm will be explained.

3.3.1 Energy production background

For the production of electric energy a solar energy production system is installed. The solar collectors have a combined power of 91.000 Watt peak and are installed on different roofs with different directions and angles. The solar collectors are connected with an inverter and so the electric energy is ready to use or to be sent to the grid. According to Garlich (2013) the electric production

can be calculated by doing the installed power times a factor. This factor is depending on the location where the solar system is installed. For the Netherlands this factor is around 0.88 according to Garlich (2013). In other words, a production plant with an installed power of 1000 Watt peak will produce around 880 kWh of electric energy per year. This is a very save calculation for salesmen so that their sold products will almost always reach the quantity the buyer expects.

Another way to calculate the produced energy is by putting an efficiency factor on the irradiation of the sun on a certain surface. The efficiency factor is the efficiency of the solar panels in transforming the absorbed energy from the sun into electrical energy. According to Dimroth (2013) the highest achievable efficiency for solar collectors is 44.7%. However these panels are not on the market yet and these results have been achieved under optimal conditions in laboratories. For solar collectors which are available to buy on the market for normal use in the Netherlands, the best efficiency is around 21.5% according to Hillege (2014).

To calculate the benefits of the solar installation, it is important to know what kind of system is installed and which kind of subsidies and arrangement are relevant. SSE (or in Dutch SDE) stands for stimulation sustainable energy and is a governmental measure to support the production of sustainable energy. This measure is specially taken for the group of higher energy consumers and producers who are not allowed to do netting. This means that they are not allowed to cross off the production and consumption against each other. Netting is the most profitable way of producing energy but for users above a capacity of 3*80 Ampere it is not allowed to do so.

SSE is a measure on which entrepreneurs can enrol their selves to get the support. The height of the support is depending on the moment of enrolment and the average price paid for the electric energy by the energy companies. This is called the corrective amount. The SSE makes sure that the price is high enough that it will be profitable for the entrepreneur so that he will install solar panels. This will be better explained in the next example.

An entrepreneur scaled in the high energy consumers group wants to have a solar installation of 10 kilowatt peaks. He tries to get SSE on this installation but the height of the support depends on the moment of enrolment. This can be seen in table 2.

Table 2 Prices for electric energy in SSE - Rijksdienst voor ondernemend Nederland(2014)

	Fase 1 Vanaf 1 april 09:00	Fase 2 Vanaf 12 mei 17:00	Fase 3 Vanaf 16 juni 17:00	Fase 4 Vanaf 1 september 17:00	Fase 5 Vanaf 29 september 17:00	Fase 6 Vanaf 3 november 17:00	Basisenergieprijs	Voorlopig Correctiebedrag 2014	Max. vollasturen per jaar	Max. looptijd Subsidie (jaren)	Uiterlijke termijn ingebruikname (jaren)
Zon	Basisbedrag per fase (€ / kWh)						(€ / kWh)				
Zon-PV ≥ 15 kWp	0,070	0,080	0,090	0,110	0,130	0,147	0,044	0,054	1000	15	3

For instance the entrepreneur enrolls on the 10th of September in phase 4. Then he will get a price of 0.11 euro per kilowatt-hour. Would he have enrolled himself on the 15th of May, he would have get 0.08 euro per kilowatt-hour for instance. However now the price paid for one kilowatt hour is 0.11 euro. The average price paid by the energy companies, or in other words the corrective amount is

equal to 0.054 euro per kilowatt-hour. The subsidy given to the owner is the difference between 0.11 and 0.054 euro per kilowatt-hour which is equal to 0.056 euro per kilowatt-hour. The corrective amount will be set every year by the government and so the subsidy will be different every year. However the measure will continue for 15 years. There is also a maximum amount of subsidy available for every specific case calculated with the maximum full load hours of 1000. This means in this example that the maximum amount of subsidized kilowatt-hours is equal to the installed capacity of 10 kilowatt peaks times the full load hours of 1000. So in this case the maximum subsidy will be 10.000 kWh times 0.056 is equal to 560 euros. However the total earnings for the solar collectors will be equal to 10.000 kWh times 0.11 is equal to 1.100 euros.

As can be seen in Table 1 the electricity prices have been constant since 2007 for the bigger consumers. Here it can be seen that the electricity price for the range 2.000-20.000 MWh has been more or less equal to 0.104 euro per kilowatt-hour. However according to Nuon (2014) some extra taxes have to be paid over this electricity price; Energy tax and a charge for storage of renewable energy. This means that per kWh extra taxes have to be paid and so the electricity becomes more expensive than 0.104 euro per kilowatt-hour. This extra payment for the energy tax and the charge goes stepwise. If the usage becomes higher, the tax goes down per kilowatt-hour. This can be seen in table 3.

Table 3 Additional energy costs

Rates for electricity including 21% tax	Energy tax per kWh	Charge for storage of renewable energy per kWh	Total energy tax per kWh
First 10.000 kWh per year	€0.1434	€0.0028	€0.1462
10.001 till 50.000 kWh per year	€0.0522	€0.0033	€0.0555
50.001 till 10.000.000 kWh per year	€0.0139	€0.0008	€0.0147

With this extra information it can be calculated that the price for electric energy varies. Namely the most expensive first step with a price of 0.104 and 0.1462 tax is equal to 0.2502 euro per kWh and the cheapest step with a price of 0.104 and 0.0147 is equal to 0.1187 euro per kWh.

3.3.2 Energy production case farm situation

Solar collectors

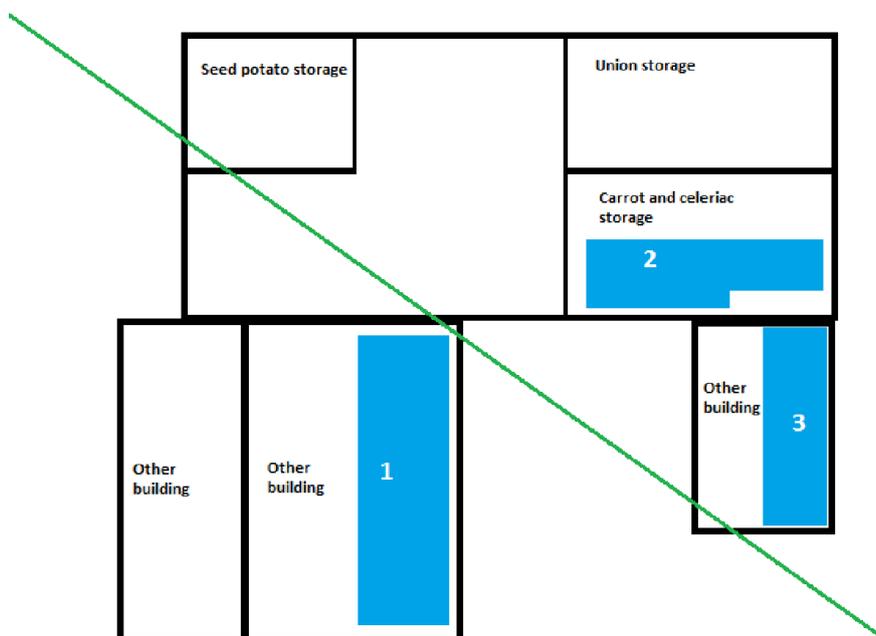


Figure 12 Map of the location with also the other buildings

In figure 13 a map of the farm can be seen. On this map the new storage facilities can be seen but other older buildings as well. The green line in the middle represents the north-south line, so the orientation of the building can be seen as well. North is on the upper left and south is at the lower right. The blue numbered squares represent the solar collector planes that are installed.

Number 1 is a plane of 165 solar collector panels (11 x 15). These are placed on a roof with slope 35° orientated towards the south-south-east. The azimuth angle is equal to 30° .

Plane number 2 consist out of 110 solar collector panels. (8 x 10 + 6 x 5). These are placed on the roof of the carrot and celeriac storage and have a slope of 25° and are orientated towards the south-west-west with an azimuth angle of -60° .

Number 3 has an azimuth angle of 30° as well like plane number 1 but has a lower slope; 30° . This plane consists out of 96 solar collector panels (8 x 12).

3.3.3 Energy prices

For this farm the energy prices found in literature are representative and therefore will be used in the models.

3.4 Thesis target

The reason for this research is to come up with an optimization of the existing situation. At this moment the solar collectors produce energy and a small part of that is used instantaneously and a large part is delivered back to the grid. When the storage system needs energy it takes that from the solar panels and if that is insufficient, it takes the rest from the grid. Those two systems don't communicate with each other about what the one is producing or what the other one is consuming. In the desired situation that communication is made so that more energy is used instantaneously and less is sent to the grid. This will result in a better financial efficiency on the produced electric energy. An important role is for the control computer to compute what the actual energy production is at every moment and to calculate the maximum instantaneous use of it. This can result in a longer cooling periods, at lower power consumption, than in the current situation. However it can also result in periods where in the current situation only storage A would be ventilated, while in the new situation also storage B will be ventilated in advance. Figure 14 can be seen as an example about how this could work. The values are rather arbitrarily chosen but it gives a clear image of what may be gained.

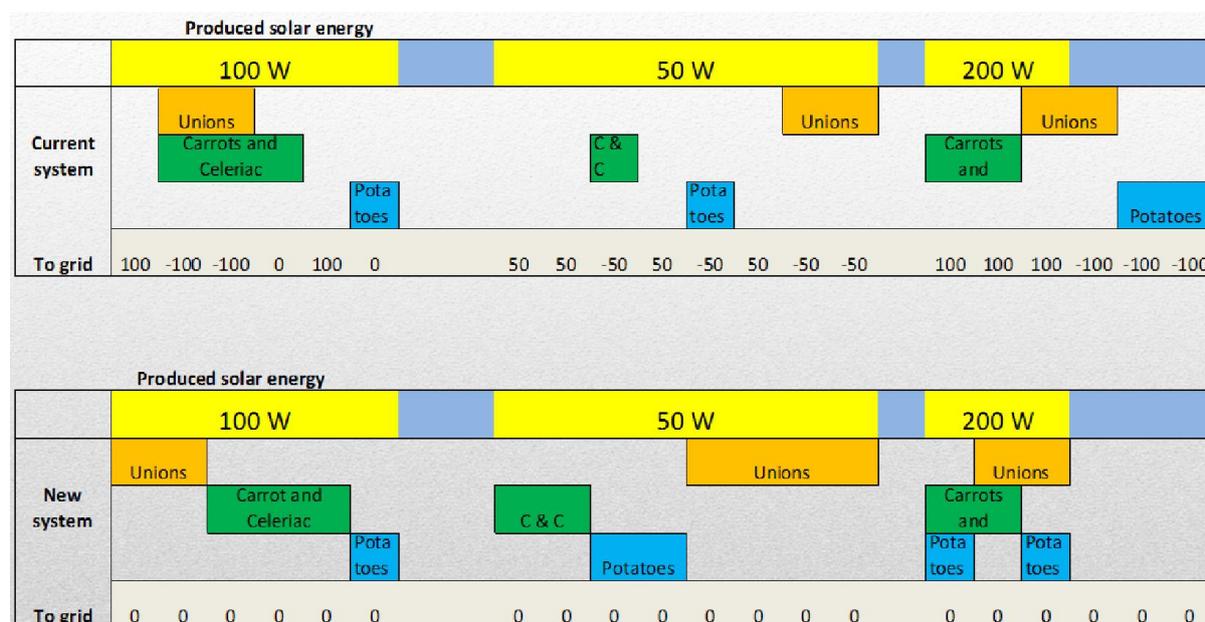


Figure 13 Control strategy current and new system

The yellow bar on top of the control examples represents the solar energy production. Every block is an energy consumption of 100 Watt. So where two blocks are activated at the same time, there is a consumption of 200 Watt. The three different colours of the block show the three different storage facilities. In the old system a lot of energy exchange with the grid occurs. However by using a different control strategy, this energy exchange can be lowered significantly as can be seen from the new system. Here the energy consumption is exactly the same but some decisions have shifted in time having a positive effect on the energy exchange. For example in the 50 Watt producing section, the cooling period is doubled from 1 to 2 hours while using the same total energy of 100 Watt hour. In this way energy exchange with the grid is prevented and so money is saved.

3.5 Sophisticated storage controllers

At this moment several storage climate controllers are available on the market. Most of them work based on measurement of the outside conditions and the conditions inside the storage and make a decision about what to do. Some climate controllers however are more intelligent. Keesman et al. (2003) considered to include the weather forecast in the control of storage facilities. By including the weather forecast it seems possible to have a large reduction in ventilation costs. Here the weather will be used to see when is the optimal moment for ventilation and when it is not. In this thesis case the weather will be used to calculate the current solar energy production instead of predicting the future. Therefore

4 Model description

To simulate the storage facilities and the energy production plant on the farm some data is needed. The most important data which is necessary is weather data. With this data it is possible to simulate the energy production by the solar collectors. Therefore the solar direct and diffuse irradiation is relevant. For the simulation of the storage facilities the outside temperature is needed. The target is to come up with models that are close to the actual situation on the farm. Figure 15 is a simplified scheme of how the case farm looks like. This scheme will be used as the basis for the models.

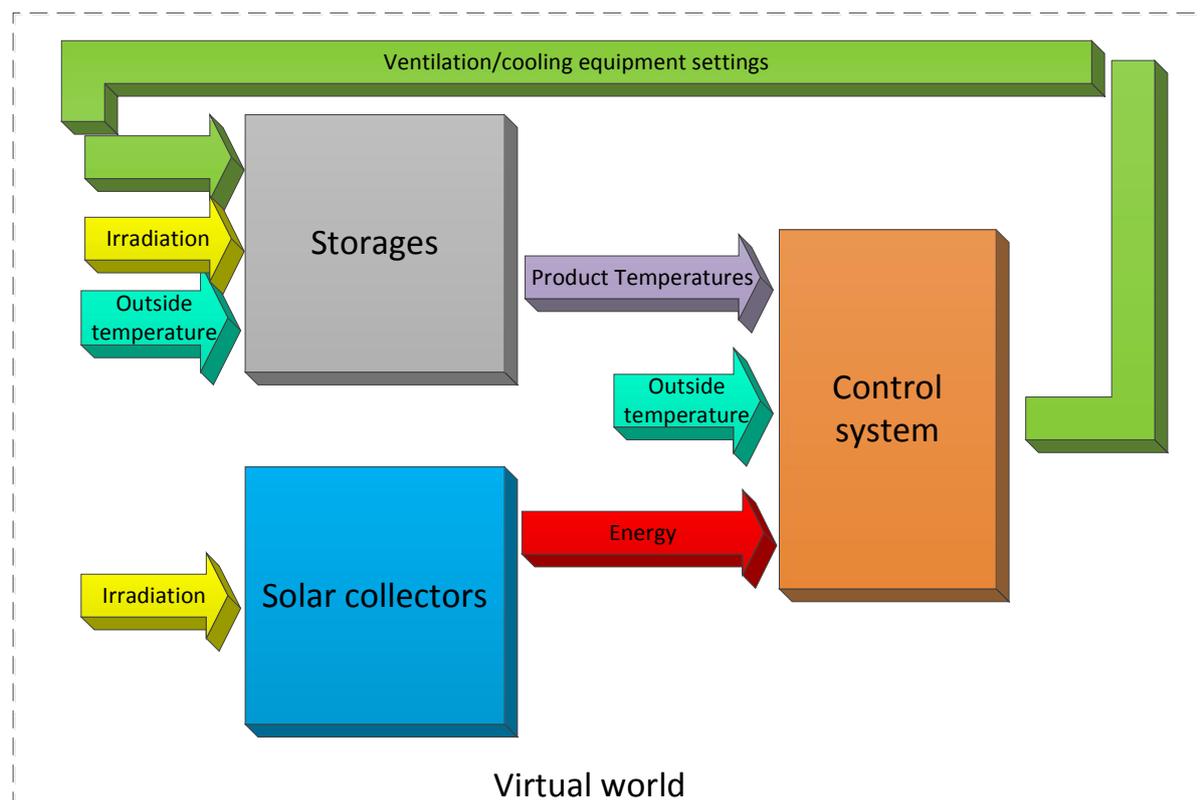


Figure 14 Basis scheme for models case farm

In figure 15 a schematic model of the storage facility and the solar energy production plant is presented. With on the one side the solar collectors and on the other side the storage facilities. The solar irradiation is taken from the weather data and put into the solar collector planes. The solar collector planes convert the irradiation into electric energy. This energy flow goes out of the model and into the control system. From the storage facilities the product temperatures are obtained and sent to the control system.

The control system will be built up in two ways in this thesis. One which takes the electric energy production not into account and one which does. However the basis of the control system is to take into account the product temperatures and the outside temperature. With this information it is possible to decide which ventilating/cooling equipment should be activate. That results in several settings which will be an input for the storage facilities again. This in turn will result in new product temperatures.

The models to simulate this process were implemented in Matlab and will be explained in further detail next.

4.1 Model of storage facilities

The modelling of the storage facilities is the next step. The storage facilities will be copied into a model that will be representative for the actual storage facilities. In the first step the dimensions and specifications of the storages will be implemented. This is done because it is more easy later to use the models for a different storage facilities. Only the dimensions and the specifications have to be changed to use it for different storage facilities as well. The energy balance and temperature calculation will be done next.

4.1.1 Carrot and Celeriac storage (Carrot_celeriac_storage.m)

4.1.1.1 Total dimensions

The first step in this function is to determine the total dimensions of the storage. This is done on the hand of four dimensions; length, width, height in the side and the height in the middle of the building where the ridge is. From these dimensions the volume of the storage can be calculated. This is the inside volume.

4.1.1.2 Storage specifications

The next step is to determine in more detail what is inside the storage. In this case there has been chosen for 810 boxes of carrots and 480 boxes of celeriac. These numbers are chosen because the average yield per hectare times the hectares that should be stored inside this storage equals 810 boxes of carrots and 480 for the celeriac. Then the volume of a single box is calculated. The boxes have always fixed dimensions of 1.60 m * 1.20 m * 1.20 m. However in the height the dimensions of the pallet should be subtracted so the actual volume is 1.60m * 1.20 m * 1.05 m. This makes that every box has a volume of 2 cubic meters. With the number of boxes and the volume of one box the volume of air can be calculated inside the storage by using formula 1.

$$\text{Volume of air} = \text{Total volume of the storage} - \text{Total volume of the boxes} \quad [m^3] \quad (1)$$

With the found information during the literature research about the density of the products, the total amount of stored product can be calculated with formula 2.

$$\text{Stored product} = \frac{\text{Number of boxes} * \text{volume of the boxes} * \text{density of the product}}{1000} \\ [\text{ton}] \quad (2)$$

From literature also the heat production per ton of the stored product was found so with the total stored amount of product, the total heat production can be calculated with formula 3.

$$\text{Total heat production product} = \text{Stored product} * \text{heat production product} \quad [W] \quad (3)$$

Finally in this part the total heat production of both products is calculated. This heat production is later on needed for the energy balance of the storage and the storage temperature calculation.

4.1.1.3 Heat balance

The heat balance is started with the calculation of the energy which is in the air inside the storage. This energy will be calculated with help of formula 4.

$$E_{in\ air} = Density_{air} * Volume_{air} * heat\ capacity_{air} * T_{in} \ [J] \ (4)$$

The second step in the heat balance is the calculation of the energy which is buffered in the product itself. In the literature research the specific heat of the products was already found. They will be used now to calculate the stored energy in the product with help of formula 5.

$$E_{in\ product} = stored\ product * T_{in} * specific\ heat_{product} \ [J] \ (5)$$

This can be done for both the celeriac and for the carrots. By adding them up the total energy content of the product can be calculated.

Also the heat production of the product is taken into account. This is calculated by converting the heat production, which is in watts, towards joules per hour by using formula 6.

$$E_{production\ product} = Total\ heat\ production\ product * 3600 \ [J] \ (6)$$

The following step for calculating the heat balance is to calculate the heat transfer through the walls and through the roof. First the surfaces of the walls and the roof will be calculated with help of the dimensions of the storage. The next step is to calculate the transfer of energy through the walls. In this calculation also a term for the transfer between the union storage and carrot storage has been taken into account. This whole calculation is represented by formula 7 and 8.

$$E_{transferwall} = U * surf_{wall} * (T_{in} - T_{out}) + U * surf_{wall\ with\ unions} * (T_{in} - T_{unions}) * 3600 \ [J] \ (7)$$

$$E_{transferroof} = U * surf_{roof} * (T_{in} - (T_{out} + Re * a * Solar_{irradiation})) * 3600 \ [J] \ (8)$$

Where U is the heat transfer coefficient of the walls and roof, Re is the thermal resistance, a is the absorption coefficient for shortwave radiation and the $Solar_{irradiation}$ is the direct irradiation from the sun.

The last step is what happens when the mechanised cooling is activated. Inside this storage there are three evaporators installed. Every evaporator has a cooling capacity of 51300 Watts. So the energy extracted by the cooling can then be calculated by formula 9.

$$E_{cooled\ extracted} = number\ of\ activated\ evaporators * cooling\ capacity * 3600 \ [J] \ (9)$$

This energy will be taken away from the storage.

4.1.1.4 End conditions

Finally with all the calculated energy flows it is possible to calculate the conditions at the end of one time step (=1 hour) in the model with formula 10. The first action is to see what the energy content of the storage is at the end of the hour.

$$\frac{E_{end}}{\Delta t} = E_{in\ product} + E_{production\ product} - E_{total\ transfer} - E_{cooled\ extracted} \quad [J] \quad (10)$$

According to the formula for the energy content of a product $Q = m * c * T [J]$ it is possible to calculate the new product temperature with formula 11.

$$T_{in\ new} = \frac{E_{end}}{(Stored\ carrot * 1000 * Specific\ heat\ carrot) + (Stored\ celeriac * 1000 * Specific\ heat\ celeriac) + B} \quad [C] \quad (11)$$

Where B is equal to: $Density_{air} * Volume_{air} * heat\ capacity_{air}$

This temperature is going out of the storage model again to give information for the system what the storage temperature is.

4.1.2 Seed potato storage (Seed_potato_storage.m)

The seed potato storage shows large similarities with the model from the carrot and celeriac storage. First of all also the dimensions of the storage are determined. The second step in this program is determining the heat exchanging surface. The third step is setting the storage specifications again where place is for 450 boxes of seed potatoes. The biggest difference between the seed potato storage and the carrot and celeriac storage can be found in the part where the heat balance is calculated.

4.1.2.1 Heat balance

Just like the heat balance of the carrots and celeriac, the calculation starts with calculating the energy of the air, the energy stored in the unions, the heat production and the heat exchange through the walls. This is all calculated in a similar way like the heat flow in the previous program. The only difference in this part is that the seed potato storage is not sharing a wall with a different product but only exchanges with outside air. However here is a difference in programs because the seed potatoes can be ventilated with outside air as well. To calculate the exact energy flow from ventilation it is best to take every energy flow separately.

When there is ventilation with outside air, there are several energy flows. One is the air coming in from outside with a certain energy content and another is the energy content from the air that is going from inside to outside. The difficult part of this calculation is that from the ventilation flow, a fraction of the air can come from outside and a fraction can come from inside. First the difference between outside and inside energy content of the air will be calculated with formula 12.

$$\Delta E_{air} = E_{air\ outside} - E_{air\ inside} \quad [J] \quad (12)$$

The next step is to calculate how much energy flows from inside to outside with formula 13.

$$E_{vent} = Van_{capacity} * Van_{nr} * fraction_{outside\ air\ for\ ventilation} * \Delta E_{air} \quad [J] \quad (13)$$

This ventilation term is added to the calculation of the energy content of the storage at the end of the time step. In this way the energy content calculation is completed and so it is possible to calculate the new seed potato temperature inside the storage in an identical way like the carrot and celeriac storage.

4.1.3 Union storage (Union_storage.m)

The union storage shows large similarities with the potato storage. Here the dimensions of the storage and the heat exchanging surface are determined first. The storage specifications however are a bit different than they were in the case of the other two storage facilities. Here the unions are not stored in boxes but in a bulk storage. The dimensions from the bulk are given first and then the specifications for the ventilation channels are calculated. These ventilation channels are half round with a decreasing height over a certain distance. The volume of the channels is subtracted from the bulk volume and so the net union bulk volume can be calculated.

The heat balance is calculated in a similar way as the other products. Here there is also a term in the transfer energy for the wall between the carrot and celeriac storage. The rest of the program calculates again the energy content of the storage and the end of the simulation step of 1 hour and the new temperature of the unions.

4.2 Electric energy generation (Solar_collectors.m)

This sub model needs the instantaneous direct and diffuse solar irradiation to work and will give as an output the produced energy in watts over all the three solar collector planes. The efficiency of the solar collectors is first set equal to the value found in the literature of Hillege (2014); 21.5%.

The next step is to calculate the elevation angle of the sun and the azimuth angle of the sun at a specific solar time for the Netherlands. It is possible to calculate these by using formulas from van 't Ooster (2012). First the hour angle is calculated (formula 14) and the suns declination (formula 15).

$$\text{Hour angle} = 15 * \text{Hour}_{day} [h] \quad (14)$$

$$\text{Suns declination} = 23.45 * \sin\left(360 * \left(\frac{(284 + \text{Day}_{nr})}{365}\right)\right) [^\circ] \quad (15)$$

From these two, and the latitude of the Netherlands, it is possible to calculate the elevation angle of the sun with formula 16. After this calculation, it is also possible to calculate the azimuth angle of the sun by using formula 17. This azimuth angle of the sun will be used to calculate the irradiation on every single surface with solar collectors.

$$\begin{aligned} \text{Elevation angle}_{sun} &= \sin^{-1}((\sin(\text{lat}_{nl}) * \sin(\text{suns declination})) \\ &\quad - (\cos(\text{lat}_{nl}) * \cos(\text{suns declination}) * \cos(\text{hour angle}))) [^\circ] \quad (16) \end{aligned}$$

$$\text{Azimuth angle} = \sin^{-1}\left(\frac{\cos(\text{suns declination}) * \sin(\text{hour angle})}{\cos(\text{Elevation angle}_{sun})}\right) [^\circ] \quad (17)$$

The last step is to calculate the solar irradiation on a specific surface. First the azimuth angle of the surface itself will be given and the slope of the roof. The second step is to calculate the angle of irradiation on the surface with formula 18:

$$\text{angle of irradiation} = \cos(\text{elevation angle}) * \cos(90 - \text{slope}) * \cos(\text{azimuth}_{sun} - \text{azimuth}_{surface}) + \sin(\text{elevation angle}) * \sin(90 - \text{slope}) \quad [^\circ] \quad (18)$$

With the angle of irradiation and the solar irradiation perpendicular on the earth's surface it is possible to calculate the irradiation on the specific surface. In this calculation the direct and the diffuse irradiation have different effects as can be seen in formula 19.

$$\text{Irradiation} = \text{Direct irradiation} * \text{angle of irradiation} + \text{diffuse irradiation} \quad \left[\frac{W}{m^2} \right] \quad (19)$$

Now the irradiation has been calculated per square meter of surface. By multiplying this by the actual solar collector area size and the efficiency of the solar collectors it is possible to calculate the actual produced energy from the specific solar collector plane.

This calculation has been done for all three solar collector planes and at the end summed up to calculate the total energy production on that specific time. For ease of computation, the total produced energy in Watts is multiplied by 3600 to obtain the total energy in Joules obtained over 1 hour which is the computational time step.

4.3 Main screen (Main_screen.m)

The main screen is the virtual world implemented as the overall Matlab program. Every sub model gets its inputs from here and delivers its outputs to it. The program starts with the choice of which simulation should be performed. By entering a 0 here, the program runs the old control system case. By entering a 1 here, the new control system is simulated.

The next step in the main screen is where the weather data come in and where initial conditions and parameter values are determined.

In the next part economics are determined. Here the values for the subsidy and the energy costs and benefits are specified.

Next the main loop starts which for every hour of the year calculates storage temperatures, energy demands and financial benefits. The next thing in this loop is to determine whether the storage is filled with product or whether it is empty. Dates have been chosen in line of expectation. When this date is reached, the storage temperature will be set to a value low value so that the cooling system does not take any action because the temperature is already at a low level. By doing this it makes sure that the control system will activate the cooling equipment. The model starts calculating at the first of September. Then the unions and seed potatoes will be harvested so those storage facilities will be filled. Until the first of November, the carrot and celeriac storage will be empty.

Next the model calculates the produced energy by the solar collectors. When the energy flow for that hour is known it is added to an energy counter. This counter is necessary because it controls when the produced quantity reaches the limit of energy on which subsidy can be obtained. If it goes beyond that limit, the subsidy per kilowatt hour will be set to 0. Then the subsidy amount of that hour will be calculated by multiplying the produced energy by the subsidy price.

The next step executes the control model. The case selected at the top of this screen will be chosen and the control system will decide which equipment should be activated or deactivated. From the control model, also the nett energy flow is obtained. If this flow is negative, then extra energy should be taken from the grid. If this flow is positive then energy is left and can be sold to the grid.

The energy tax should be calculated first if energy is taken from the grid before the financial costs or benefits from this flow can be calculated. Because the energy tax builds up stepwise, the energy taken from the grid will be counted. When the energy tax on the energy taken from the grid is known, it is possible to calculate what the costs of the energy flow are. That is the price paid to the energy company for the energy plus the tax paid to the government. However when energy is left, it will be sold to the grid against the selling price. The financial result of each time-step and the subsidy will be added to the total financial result. If nett energy is taken from the grid the financial result of the time-step will be negative. When energy is delivered towards the grid, the financial result of the iteration will be positive.

The next part of the loop executes all the models of the storage facilities. After execution new storage temperatures will come out. These temperatures will be used during the next time-step.

Finally, the large vectors will be filled in with the information from the iteration. These vectors will be filled in till the whole year is filled in. Afterwards, these vectors can be used to show the results (graphically).

4.4 Control system

The control system is the Vision Control computer that calculates which equipment should be activated and which should not. The only information needed to do this is the temperature and the electricity production.

4.4.1 Old case (Control_system_old_case.m)

The old case means that the computer only looks to product temperatures. Every product has a certain desired temperature where the product should be stored at and a certain allowed deviation. This deviation determines the upper bound temperature and the lower bound temperature. For instance, the unions should have a storage temperature of 4.5 °C and have a deviation of 0.3°C. In this way are the upper bound temperature 4.8°C and the lower bound temperature 4.2°C. If the temperature in the old case reaches 4.8°C, the computer activates equipment which will bring down the temperature to 4.2°C. Which equipment this should be, will be determined later in this model.

The first part in this model is to set the desired temperatures for every storage and their deviation. This can be seen as the settings which will be implemented by the farmer. First the third part will be explained and then the second part of this model for better insight in the model.

The third part is to determine which actions should be done in this time-step. This will be done for every storage in a similar way. It will be explained for the union storage but the same holds for the other storage facilities.

For the union storage facilities three things can happen. The union temperature is higher than the upper bound temperature, the union temperature is between the temperature bounds and the union temperature is below the under bound. The first step here is to see if the product temperature exceeds the upper bound temperature. If that is the case, all fans will be activated for ventilation. The next thing is to determine if it is possible to ventilate with outside air or not. This can be determined by looking if the outside temperature is lower than the union temperature. If this is the case, the fraction of outside air into the air mixture with inside air will be determined. The mixture air will have the

right temperature for ventilating the unions. The fraction of outside air is set to a limit of 1 because it is not possible to use more than 100%.

However, when it is not possible to use outside air for cooling, the artificial cooling is needed and will be activated using both evaporators. When the artificial cooling is activated, it also means that the storage will close entirely so the fraction of outside air for ventilation will be 0.

Then the cooling process chosen by the first step will continue until the union temperature has reached the lower bound temperature and all the cooling processes will stop. When everything is switched off by this function, the temperature will increase slowly until it reaches the upper bound temperature again.

However it could occur that the outside temperature is within the temperature boundaries but lower than the union temperature. In this way the storage will start cooling with outside air but will never reach the lower bound temperature and therefore will cool forever. Therefore in the second part of the program a reset is implemented. This reset checks if the outside temperature is between the temperature boundaries and if the outside air ventilation system is activated. If all this is true, the outside air ventilation system will be deactivated. Then in the next time-step it will be determined again if some cooling actions are needed. The same holds for the potato storage.

The last part will be used to do some energy calculations. First the energy production of joules per hour will be transformed into watts. All the energy consumption by the activated equipment will be subtracted from the energy flow which will result in an energy result at the end. This energy result will be used for the financial calculation in the main screen. The solar energy production in this case is more or less passive. The only thing that will happen to it is that the energy consumption is subtracted from it.

This procedure just is almost the same for the potato and carrot and celeriac storage. The only difference for the carrot and celeriac storage is that it is not possible to ventilate with outside air. So if the maximum temperature reaches the upper bound, the artificial cooling will activate immediately.

4.4.2 New case (Control_system_new_case.m)

The new case however works more sophisticated. In this case the computer looks not only to temperature but also to solar energy production. So the solar energy production becomes more active within the system. To maximize the instantaneous use of produced energy, the computer should work a bit different. One of these differences is that the moment the temperature is above the temperature upper bound, it does not necessarily mean that the product will be cooled down till the lower bound temperature. How this works will be explained later on.

The first part in this control system is again for the farmer to set the set point temperatures and the deviations.

The second part is an additional part with respect to the old system. Here a temperature vector is made containing the difference between the actual product temperature and the temperature upper bound. The smaller this difference, the earlier this storage has to be cooled in future. This will be used later to determine which storage has a privilege, or priority, to cool if there is still energy left after the necessary cooling. The idea of this can be seen in table 4.

Table 4 Example of temperatures and temperature difference

	<i>Minimum temp. [°C]</i>	<i>Maximum temp.[°C]</i>	<i>Actual temp. [°C]</i>	<i>Temp gap [°C]</i>
Union temperature	4.2	4.8	4.7	0.1
Potato temperature	3.7	4.3	4.1	0.2
Carrot and celeriac temperature	0.9	1.1	0.9	0.2

From table 4 it can be seen that the temperature gap is the difference between the maximum allowed temperature and the actual temperature. These gaps will be put in a row vector and will be ordered from low to high. In this case the union storage facility will have priority 1 followed by the potato storage facility and the storage facility from the carrots and celeriac.

The next thing to do is to convert the energy produced by the solar collectors from joules per hour into Watts. This information will be used later on in the model to calculate the energy flow left.

The next step is to reset all the equipment to off again. This cooling will not automatically cool from the temperature upper bound towards the lower bound temperature. Therefore every time-step starts with all equipment deactivated.

First the necessary cooling is determined. This is the same as the control system in the old case. Here actions are immediately taken if the temperature exceeds the temperature bounds and are therefore necessary. The only difference here is, as mentioned, that the cooling will not stop until it reaches the lower bound temperature but it will directly stop at the next time-step.

The next part is an additional part to increase the use of instantaneous produced solar energy. This part will calculate if it is possible to activate more cooling equipment in other storage facilities with respect to the available amount of energy produced by the solar collectors. A control scheme to give a better explanation of the new control system is shown in figure 16. This figure shows in large ways how the system is organized. A more detailed explanation of the new control system will be given later.

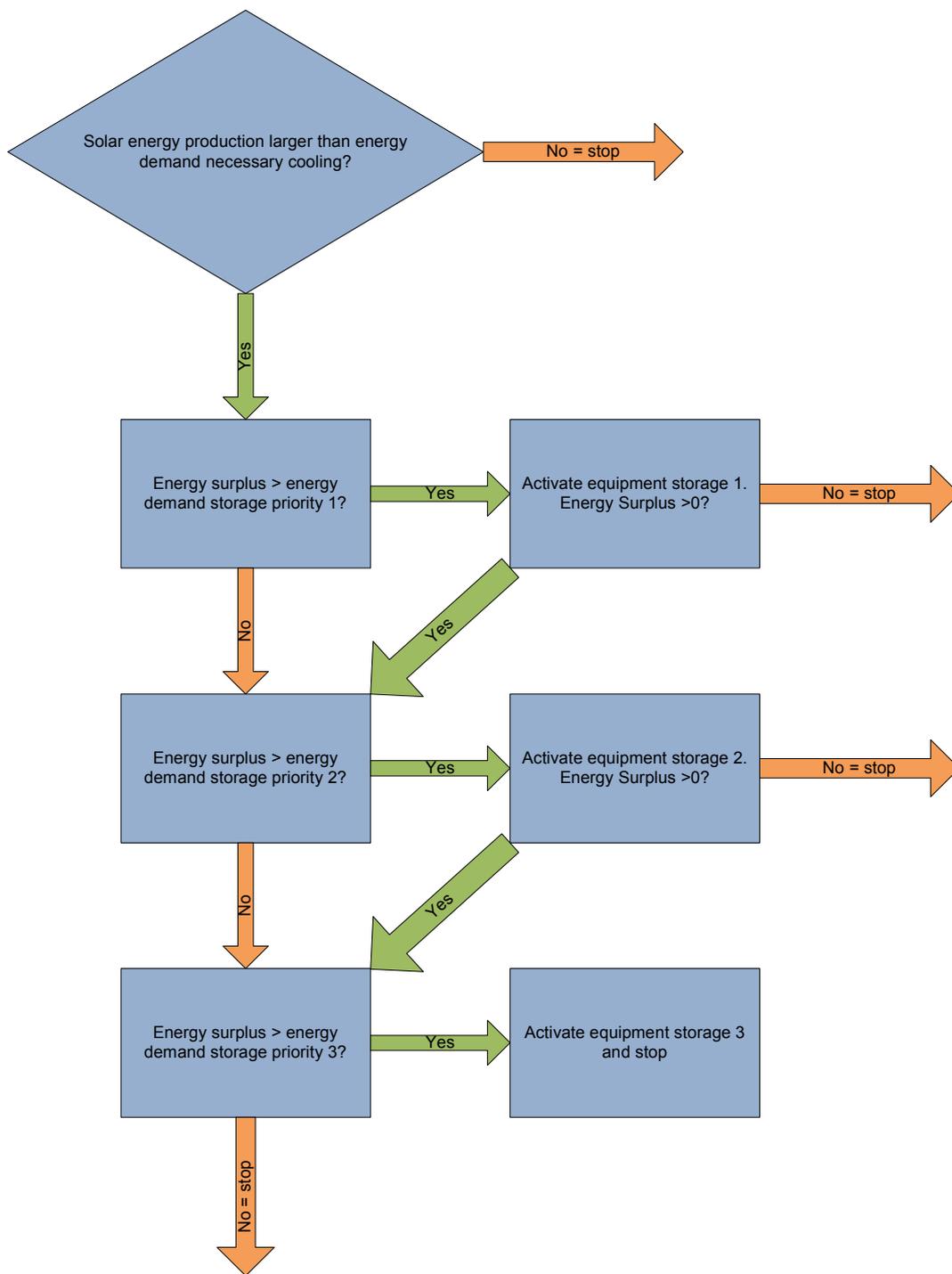


Figure 15 Additional part new control system with respect to available amount solar energy

The first thing to do is to calculate how much energy is left after the activation of the necessary cooling. If there is energy left, it will be determined if it is possible to activate equipment in the storage facility with priority 1. After activation of equipment, a new calculation for the energy surplus will be made before it goes to the next storage facility. If there is no energy left, the system will not search any further and stops.

Not only the solar energy availability is important for the activation, also the outside temperatures of course. This check will be done in a similar way as the determination of activated cooling in the old control system.

Several checks have to be done between the check if there is enough energy and the actual activation of equipment. A scheme of these checks and the to be taken actions can be seen in figure 17.

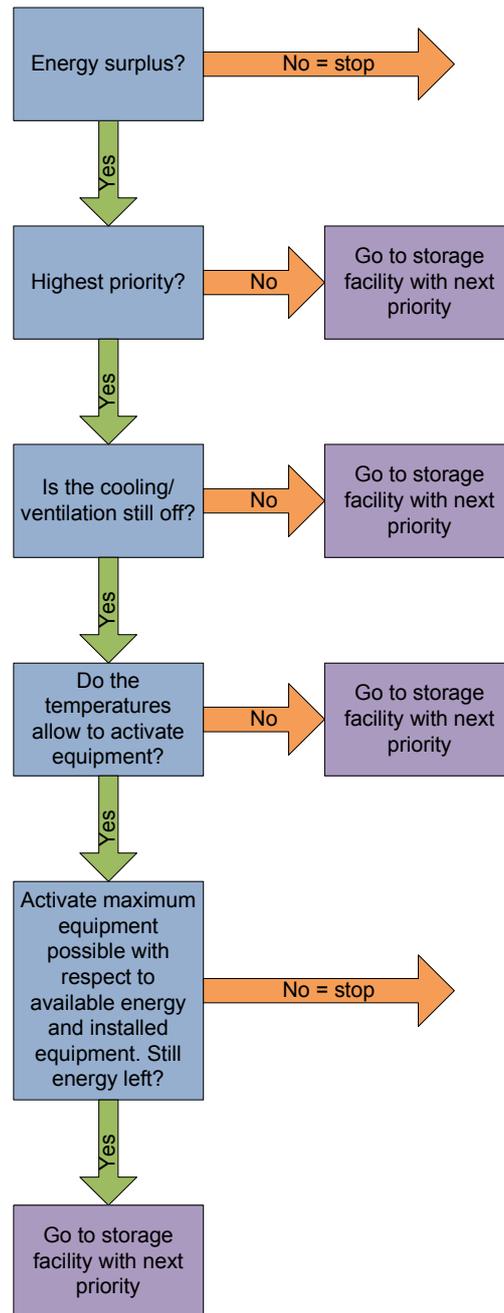


Figure 16 Representation of checks and decisions within new control system

Figure 17 shows the way the addition of the new control system works in more detail. When the step to next storage facility is directed, the same checks start at the top from figure 17 again for the specific storage with the next priority.

There are some other additions of course that will be explained now in further detail.

The first additional part is related with the way equipment can be activated. It shows large similarities with the old control system and the necessary cooling part but has some difference as well. The difference however is that not just all the fans for example will be activated immediately but that the system calculates how much fans can be activated with respect to the available solar energy. In this way the system will never need energy from the grid at that moment. The same holds for the artificial cooling. It will calculate how much evaporators can be activated and also how much fans can be activated. There should always run at least one fan if the artificial cooling is activated. The system also makes sure that not more fans and evaporators are activated than installed inside the storage.

Another addition is related with the activation of artificial cooling when there is energy left. Because artificial cooling requires a lot more energy than cooling with cold outside air, there is another check. If the outside temperature is between the temperature boundaries but still higher than the union temperature, the system will do nothing. It will wait till the union temperature is higher than the outside temperature and will cool then if there is still energy left at that moment. This prevents that the artificial cooling will be activated while this is not explicitly needed and solar energy will be wasted.

After the determination which equipment can be activated, the scheme of figure 16 starts all over again for the storage facility with the next highest priority.

The final energy result will be calculated at the end outside all the equipment status determination. This value, and all the statuses of the equipment will go out of the model towards the main screens.

4.5 Weather data and transformation (Weather_data.m)

A dataset of the weather from 2009 in the Netherlands, measured by the KNMI, is used in this research. To use the data within Matlab transformation of the data into a suitable matrix is performed.

The data were recorded every minute but they will be transformed towards a time step of 1 hour by averaging. Therefore some code has been written that takes the values from every minute and average it into hours. These averages will be written into matrix form so that the rest of the models can use them.

5 Computations and Results

This chapter presents the outcome of computations performed with the original control system and the new control system. Together the outcome of all computations determine the performance improvement of the new control system versus the original. This answers the major research question. Some interesting related results are also presented in this chapter..

5.1 Main computations and results

Using the weather data, the models of the storage facilities and the controllers, the full control system can be simulated. From these simulations several interesting results, like storage temperature patterns that are realised, as well as energy costs can be obtained. These results answer the major research questions and are presented in the first part of this chapter. The second part considers interesting related results obtained during this research.

5.1.1 Solar collector energy production

Using weather data and the model of the solar collectors the solar energy production over the year is calculated and shown in figure 18.

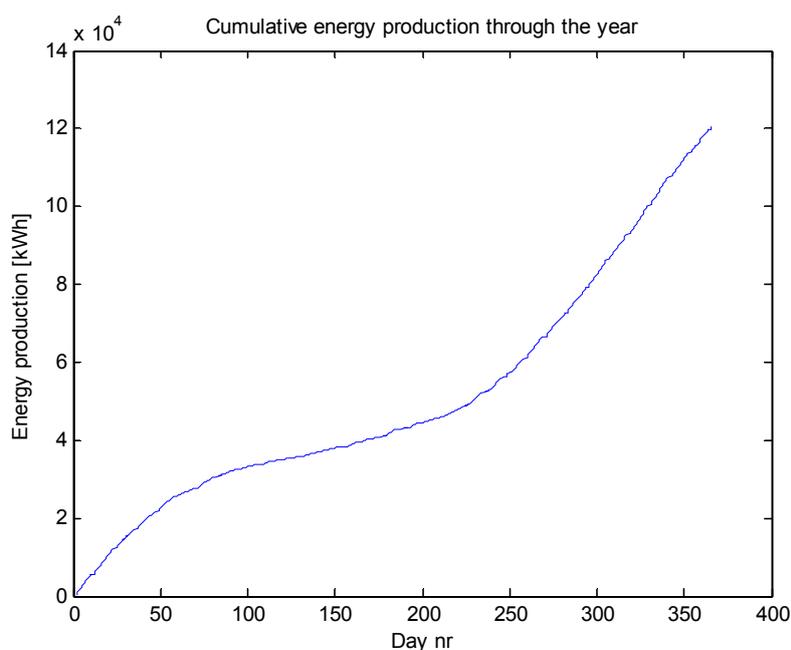


Figure 17 Cumulative solar energy production through the year

As mentioned before, the model starts at the first of September and ends on August 31. It can be seen that around day 75 the solar energy production rises slowly. The reason for this is the short days, low irradiation level and bad weather during the winter. From spring it increases rapidly again until the end of August. The three planes with solar collectors produce together slightly more than 120.000 kWh.

5.1.2 Carrot and celeriac storage temperatures

Simulation of the full control system provides storage temperatures over the year.

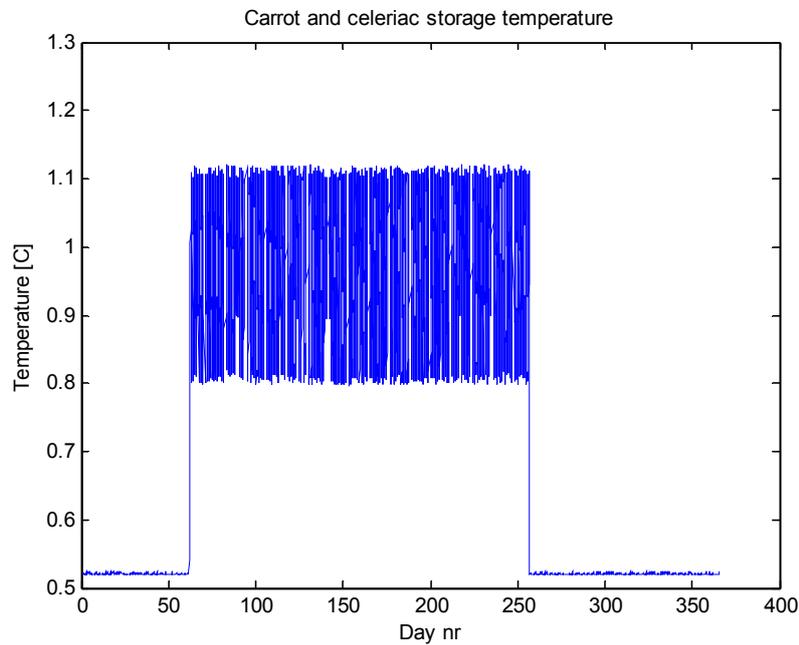


Figure 18 Carrot and celeriac storage temperature curve old control system

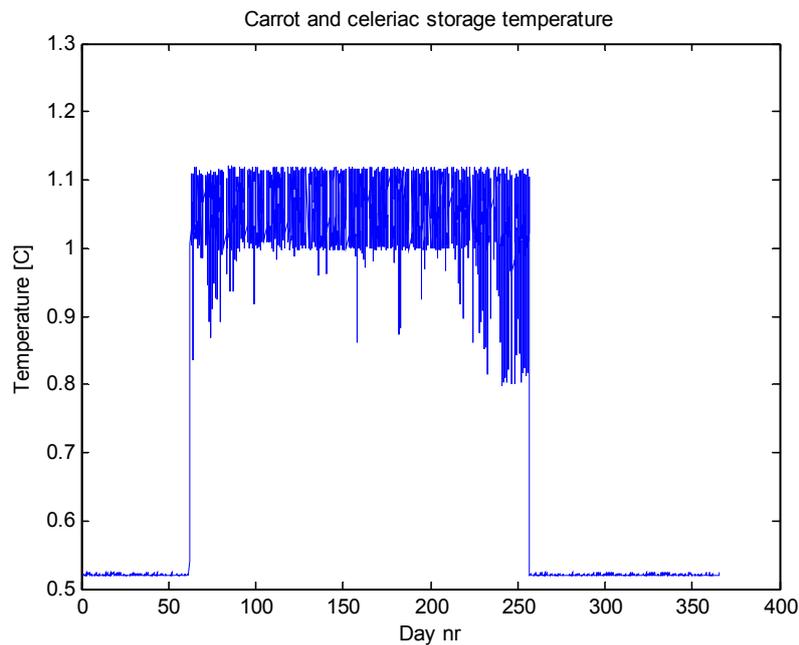


Figure 19 Carrot and celeriac storage temperature curve new control system

Figures 19 and 20 are the temperatures of the old and new control system. The difference between the systems can be seen quite well. The temperature of the old system varies between the upper bound temperature of 1.1 °C and the lower bound temperature of 0.9 °C as expected. The reason that some peaks go below 0.9 is that every time-step equals one hour and so the cooling is on too long sometimes. The time-step should be smaller to have a better result. The time-step is important because

the cooling has a high capacity so the time of cooling has a large influence on the product temperature. It is hard to see but in the graph the line goes slowly towards the upper bound for temperature and when it reaches the upper bound, the storage will be cooled until the lower bound is reached. At times where the temperatures are slightly above 0.5°C, the storage is empty.

The new control system however works differently. Here the product will be cooled if it reaches the temperature upper bound but not until it reaches the lower bound on temperature. When energy is available, it will be cooled down further. This will not happen a lot for this storage because it takes a lot of energy to cool and it is not often that this energy is still available. However in the beginning (until day 95) it can be seen and on the end as well (from day 210) This is because there is more produced energy available over there because of the spring and autumn as already have been seen in figure 18. In winter it is hardly the case that some extra cooling can be done on the available left energy because there is hardly energy produced.

5.1.3 Potato storage temperature curve

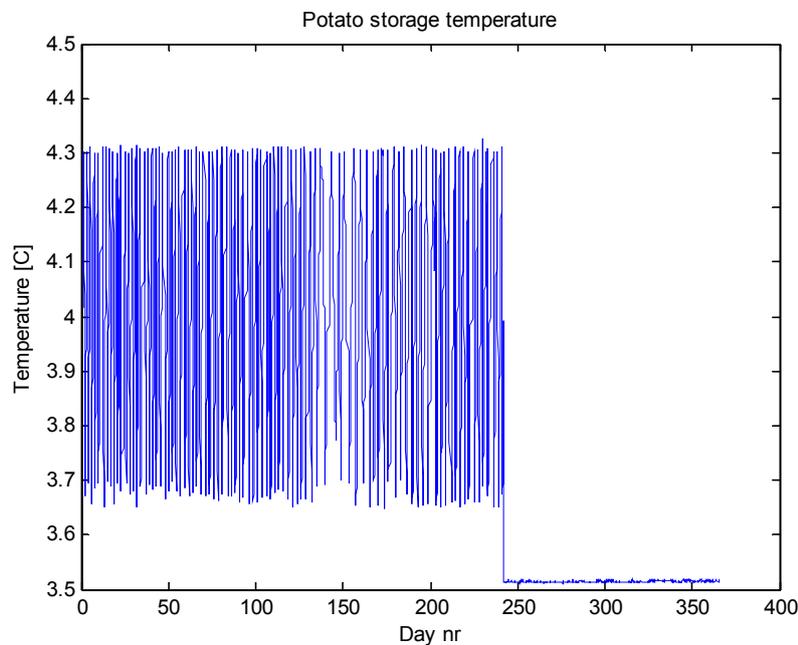


Figure 21 Potato storage temperature curve old control system

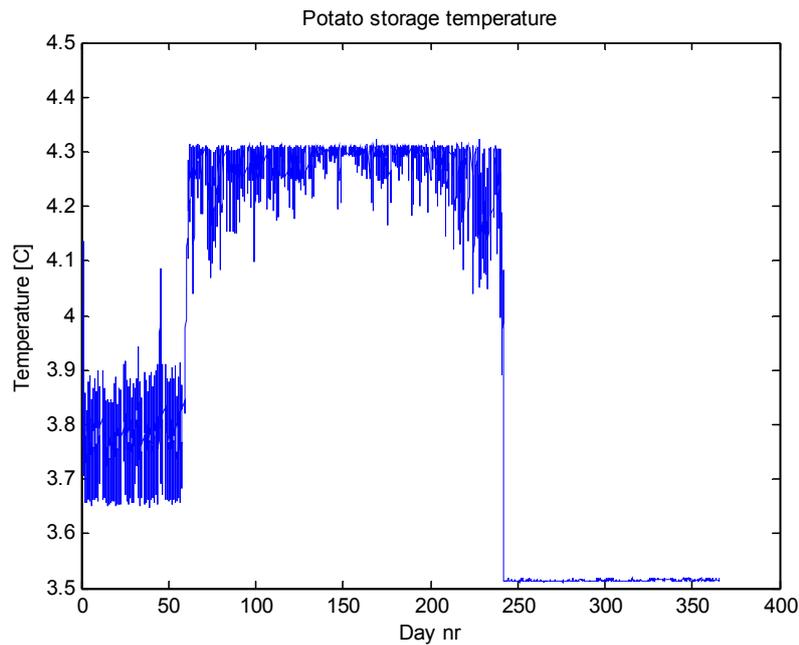


Figure 22 Potato storage temperature curve new control system

Figure 21 and 22 shows the potato temperature curves with the old and new control system. The graph of the old control system shows large similarities with the graph of the carrot and celeriac storage. Here however the storage is immediately filled with product and the temperature settings are different.

The graph of the new control system however shows a different image. It can be seen that in the beginning of the simulation, the lower bound temperature can be reached almost all the time with the solar energy production. There are two reasons that this lower bound temperature can be reached. One reason is that in that time of the year solar energy is largely available in September and October. The second reason is that the carrot and celeriac storage is still empty. As a result there is more energy available for cooling the potato and union storage. When the available energy drops and the carrot and celeriac storage is filled however, the potato temperature curve is almost all winter at the temperature upper bound. In spring when more energy becomes available again, it is possible to cool a bit further using the available solar energy.

5.1.4 Union storage temperature curve

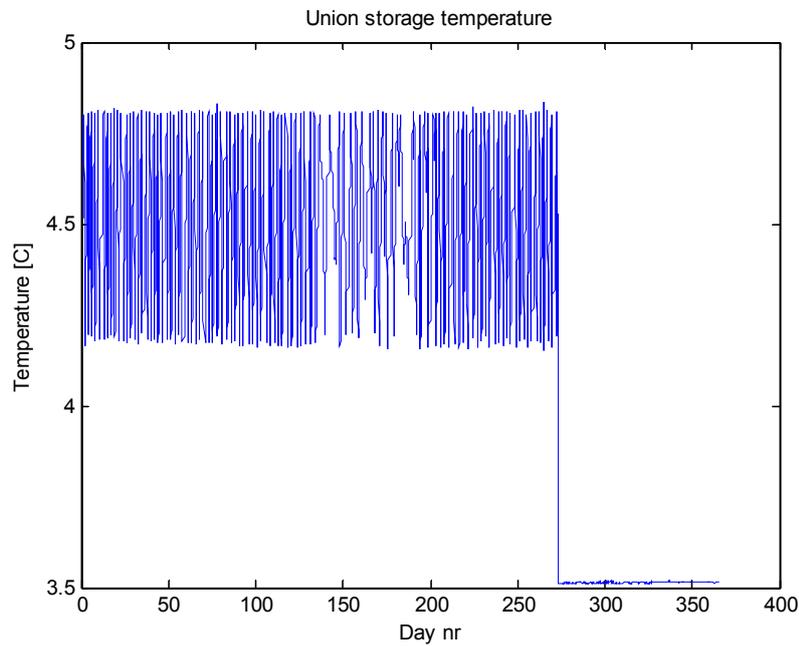


Figure 23 Union storage temperature curve old control system

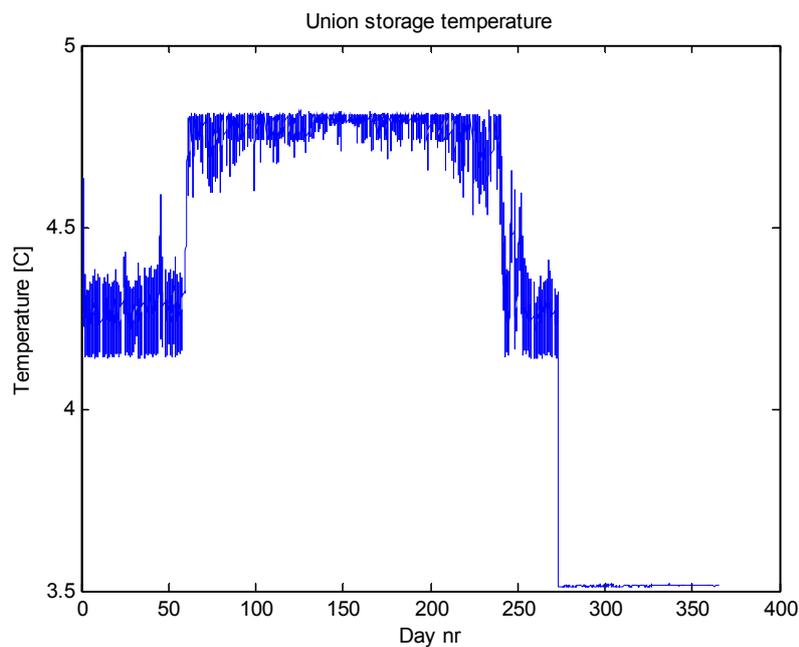


Figure 24 Union storage temperature curve new control system

In figure 23 and 24 the union storage temperature patterns can be seen. The result is more or less equal to the result of the potato storage. In the figure of the new control system at the end, it can be seen that the temperature goes towards the lower bound temperature again. The reason that this can occur is that there is more energy available due to higher solar irradiation in that time of the year. Another advantage is that the potato, carrot and celeriac storage are all empty so more energy is available to cool the unions.

5.1.5 Energy exchange

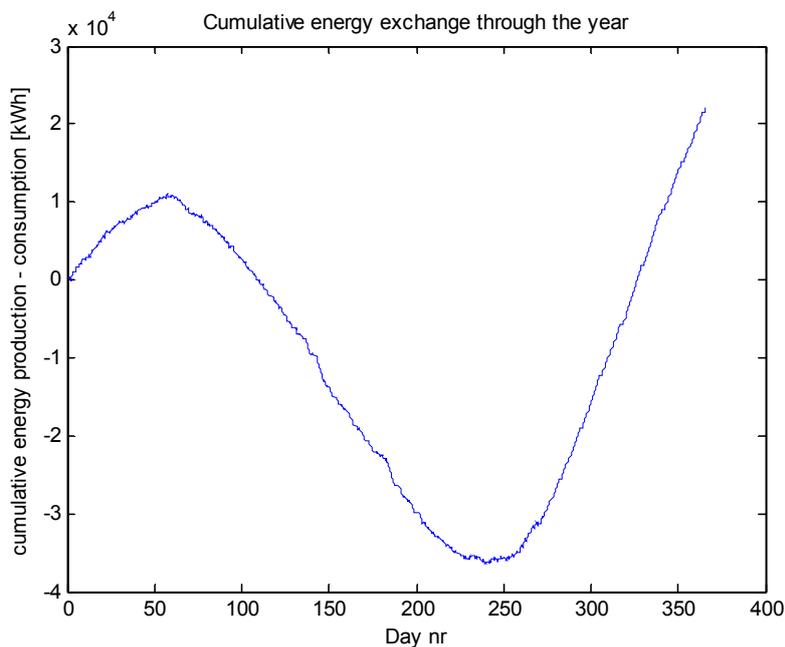


Figure 25 Cumulative energy exchange with the grid - old control system

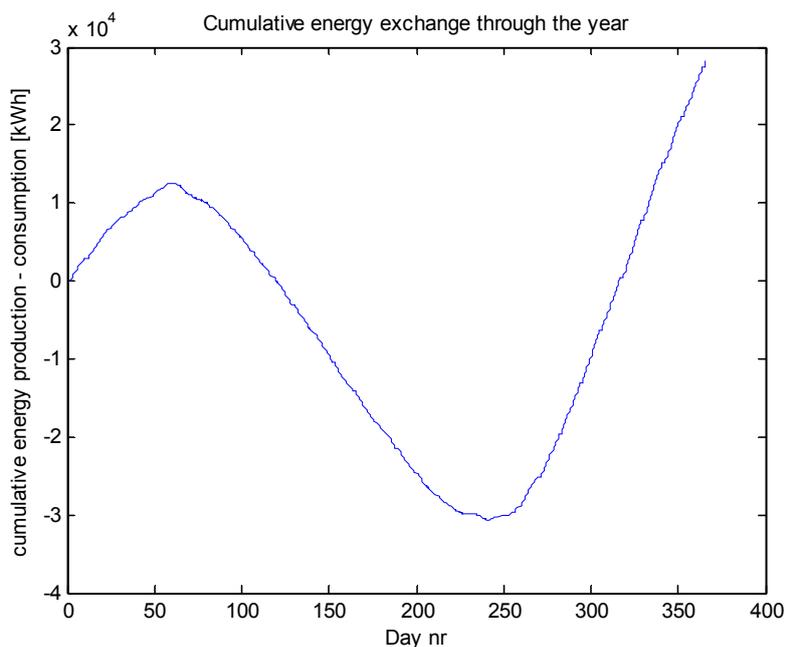


Figure 26 Cumulative energy exchange with the grid - new control system

Figures 25 and 26 represent the cumulative energy exchange with the grid. At places where the gradient is positive, the farm delivers energy to the grid. When the gradient is negative, energy is consumed from the grid. The trend over the year is more or less the same for the old control system as for the new control system but the major difference is that the peaks are lower. In the old system approximately 35.000 kWh nett is consumed at day 250 where this is for the new situation only 30.000 kWh nett. Also at the end of the year the difference can be seen. Where the old control system

has delivered 22.100 kWh to the grid at the end of the year, the new control system delivers more than 28.100 kWh to the grid. In other words, by a change in controlling the storage facilities it is possible to save 6000 kWh on a yearly basis. Or in percentage, it is possible to deliver 27.1% more energy to the grid. The farm becomes more energy efficient with this new system and this will contribute to the durability of the farm.

5.1.6 Activation hours

Another question which is important then is what the effect of the new control system is on the hours of ventilation and cooling. Lower energy consumption does not necessarily mean less cooling hours.

Table 5 Ventilation and cooling hours old and new control system

	<u>Old control system</u>	<u>New control system</u>
	<u>[h]</u>	<u>[h]</u>
Unions:		
<i>Ventilation hours</i>	1660	1792
<i>Cooling hours</i>	881	1005
Potatoes:		
<i>Ventilation hours</i>	1456	1809
<i>Cooling hours</i>	974	910
Carrots and celeriac:		
<i>Cooling hours</i>	761	910

As expected, the number of ventilation hours increases as can be seen in table 5. A ventilation hour is one where at least one fan is activated. A cooling hour is one where the artificial cooling is activated. Because the new system switches on fans independently, the number of ventilation hours will be higher. For example, with the old control system 8 fans were activated for one hour and are counted as one ventilation hour. The new control system however can switch on 4 fans during two hours to have the same amount of displaced air while counting as 2 ventilation hours.

For the cooling hours, the exact same thing happens for the unions and for the carrot and celeriac. It is now possible to switch on just 1 evaporator instead of all available evaporators at the same time.

The effect for the potato storage however seems unexpected. But is in fact quite logical. This cooling system is not split in parts and has the same capacity as in the old control system. The artificial cooling hours will decrease because the cold outside air will be used more efficient by the new control system by ventilating more with outside air. This will have a positive result on the energy demand and so the profitability of the system.

5.1.7 Financial benefits

The 6000 kWh savings of energy exchange with the grid is a large effort on a yearly basis and contributes significantly to the economic effort. The difference between economic efforts can be seen in figure 27 and 28.

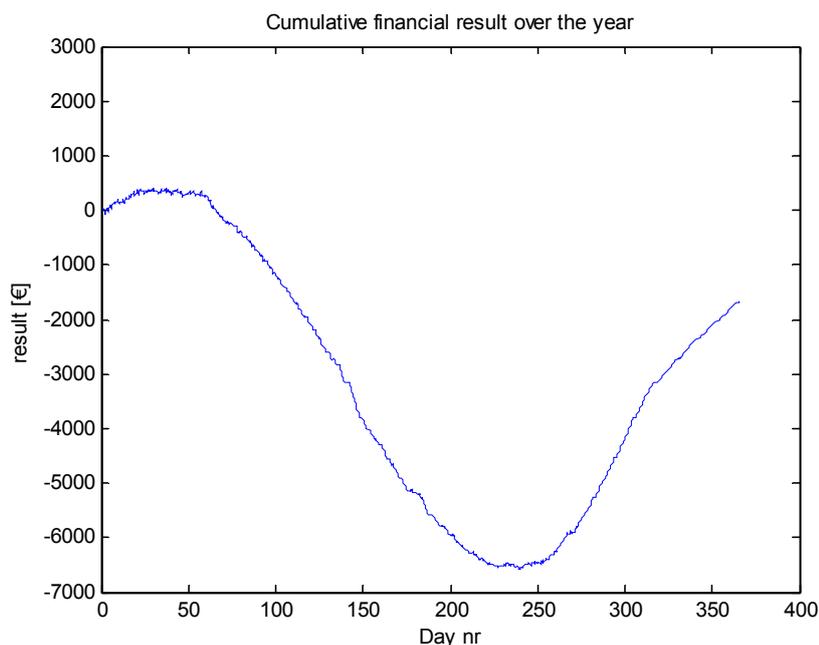


Figure 27 Cumulative energy result in euro's - old control system

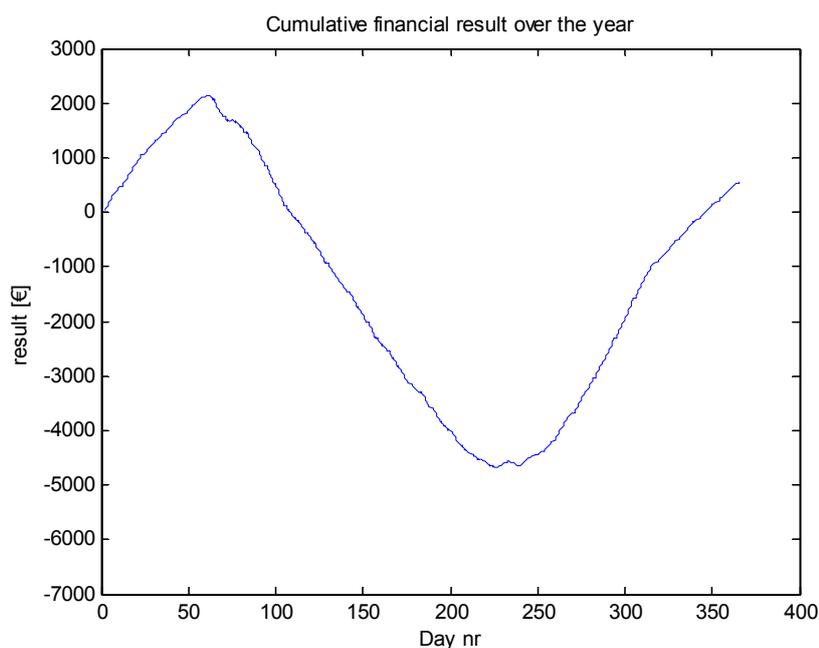


Figure 28 Cumulative energy result in euro's - new control system

Naturally the results for the economics show large similarities with the energy exchange with the grid. The value can be seen as the financial account at every moment of the year. The different ways of controlling the storage will result in an economic end result in the old system of €-1663 and in the new system of €569. This is a financial gain of more than €2200. One of the biggest improvements is reached in the first 60 days and forms the basis for the success of the new control system. The advantage here is that the storage facilities of the unions and potatoes can be cooled almost totally using the instantaneously produced solar energy and no energy has to be taken from the grid.

5.2 Additional results

Some interesting additional questions and results have been investigated and obtained up during this research. They relate to sensitivities of the control systems to several parameters and scenarios.

5.2.1 Influence of temperature deviation

It is interesting to see the effects of the temperature deviation on the control system performance. This is reflected best by the ventilating hours and financial result at the end of the year. Table 6 and 7 show the results for the original scenario and two others.

Table 6 Temperature deviations for three scenarios

	<u>Original case</u>	<u>Scenario 1</u>	<u>Scenario 2</u>
Unions	0.3	0.2	0.4
Potatoes	0.3	0.2	0.4
Carrots and celeriac	0.1	0.05	0.15

Table 7 Influence of temperature deviations on control system performance

	<u>Original case</u>	<u>Scenario 1</u>	<u>Scenario 2</u>	
Unions:				
	<i>Ventilation hours</i>	1660	1559	1411
	<i>Cooling hours</i>	881	930	893
Potatoes:				
	<i>Ventilation hours</i>	1456	1749	1422
	<i>Cooling hours</i>	974	975	933
Carrots and celeriac:				
	<i>Cooling hours</i>	761	761	761
Financial result:				
		€-1663	€-1556	€-1048

What can be seen from Tables 6 and 7 is that in case the temperature deviation is larger, less ventilation hours are needed for the unions and potatoes. Another thing which can be seen is that the cooling hours of the carrots and celeriac stay the same. This is quite logical because the same amount of energy should be taken away by the system which has the same capacity. The financial results are the most interesting. To perform a proper cost analysis however the relationship between product quality and financial benefits should also be considered. For instance, by making the temperature deviation a bit bigger as is done with the original case and scenario 2, what are the effects on product quality and how do these translate financially? If the financial loss of product quality is smaller than €615, it is interesting to take the temperature deviations from scenario 2 instead of the original case. Considering the effect of temperature deviations on product quality as well as that of product quality on financial results was outside the scope of this research. Clearly it represent an interesting area for further research.

5.2.2 Scenario and sensitivity analysis

Another possibility to use the models provided by this research is to calculate sensitivities to key parameters and external conditions and perform scenario studies. For example what happens if there is

less irradiation on a yearly basis or a change in electricity prices? Outcomes of such calculations and studies can be very interesting and useful.

5.2.2.1 Irradiation

The first scenarios that will be examined is what the effects are if there is less or more irradiation on a yearly basis. Data of the year 2009 has been used in the model. Having data of irradiation levels from other years would enable a scenario analysis. In Table 8 results of such an analysis based on artificial data obtained from the year 2009 are presented.

Table 8 Financial results for different irradiation levels

	<u>Old control system</u>	<u>New control system</u>	<u>Difference</u>
2009 – 10% irradiation	€ -2260	€ -229	€ 1831
2009 – 5% irradiation	€ -2122	€ 157	€ 2279
2009	€ -1663	€ 569	€ 2232
2009 + 5% irradiation	€ -1127	€ 1028	€ 2155
2009 + 10% irradiation	€ -743	€ 1487	€ 2230

From table 8 it can be seen that different irradiation levels have a large effect on the financial results. The largest difference is between -10% and +10% irradiation of €1517 obtained for the old system. For the new control system the difference is €1716 between -10% and +10% irradiation. All these effects are quite logical because there is less or more energy to sell and so the financial result will be different. The improvement of each different control system however stays more or less the same around the €2200. Only on very low irradiation levels the improvement between the old and new system drops.

5.2.2.2 Electricity prices

Another interesting factor is the sensitivity to electricity prices. Because this model uses two different energy prices, one for buying and one for selling it is possible to vary both of them. However it may be expected that if the price for buying increases, the price for selling increases in the same way. In this scenario analysis it is therefore assumed that both prices change by the same amount.

Table 9 Financial result for different energy prices

		<u>Old control system</u>	<u>New control system</u>	<u>difference</u>
Buying price	Selling price			
€ 0.104 -€0.03	€ 0.054 -€0.03	€ -2326	€ -276	€ 2050
€ 0.104 -€0.02	€ 0.054 -€0.02	€ -2105	€ 6	€ 2111
€ 0.104 -€0.01	€ 0.054 -€0.01	€ -1884	€ 287	€ 2171
€ 0.104	€ 0.054	€ -1663	€ 569	€ 2232
€ 0.104 +€0.01	€ 0.054 +€0.01	€ -1442	€ 851	€ 2293
€ 0.104 +€0.02	€ 0.054 +€0.02	€ -1221	€ 1132	€ 2353
€ 0.104 +€0.03	€ 0.054 +€0.03	€ -1000	€ 1414	€ 2414

From the results of the scenario analysis, given by table 9, it can be seen that the financial result with the old and new control system is better for higher energy prices. Therefore the most important factor is the higher selling price. Because the relative increase of the selling price is larger than that of

buying a better result is obtained when prices increase. The same can be seen for the difference between both systems. So in the end it can be concluded that the financial result, and so the financial performance of the control systems are better at higher energy prices. From Table 8 it also follows that the difference between the old and the new control system increases with € 61 per eurocent increase of the energy prices.

5.2.2.3 Electricity prices

Due to climate change, the outside temperature is slowly increasing. This makes the outside temperature an interesting changing factor.

For the scenario analysis a varying temperature between minus two degrees Celsius and plus three degrees Celsius was selected. This is quite a big variation with respect to climate change. The implementation of the variation is done by adapting every value for the outside temperature with the temperature variation. The results of this scenario analysis are shown by figure 29.

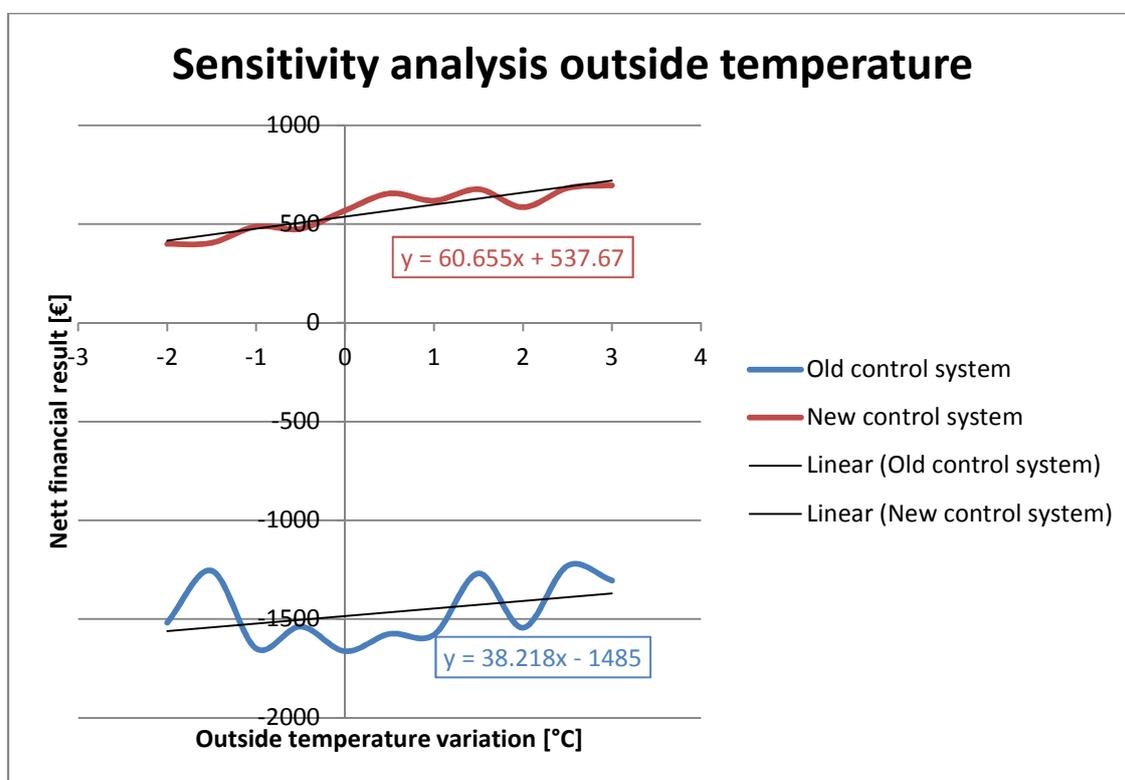


Figure 29 Financial results for both system with outside temperature variation

The financial results of both control systems increase when the outside temperature increases as can be seen in figure 29. Implementation of the regression line in the results of both systems show which system is more sensitive to the outside temperature. Figure 29 shows that the new control system is more sensitive than the old control system.

Both systems show a positive regression which means that the financial result will be higher at higher temperatures. This result is unexpected because more heat will come into the storage from outside. This same heat has to be removed again by the cooling systems. This is a surprising result and it is

suspected that the decrease in less effective ventilation hours will be replaced by high effective artificial cooling hours and therefore a small amount of energy consumption can be saved.

5.2.2.4 Smaller yield

Until now it is still assumed that all the storages are filled completely with product. However, it is possible that this won't be achieved due to lower product yields per hectare. Therefore a sensitivity analysis on the amount of stored product will be done as well. The sensitivity analysis is based on a decrease in yield of maximum 20% because years with these lower yield occur on a regular basis due to unfavourable growing circumstances. The results of this analysis are shown in figure 30.

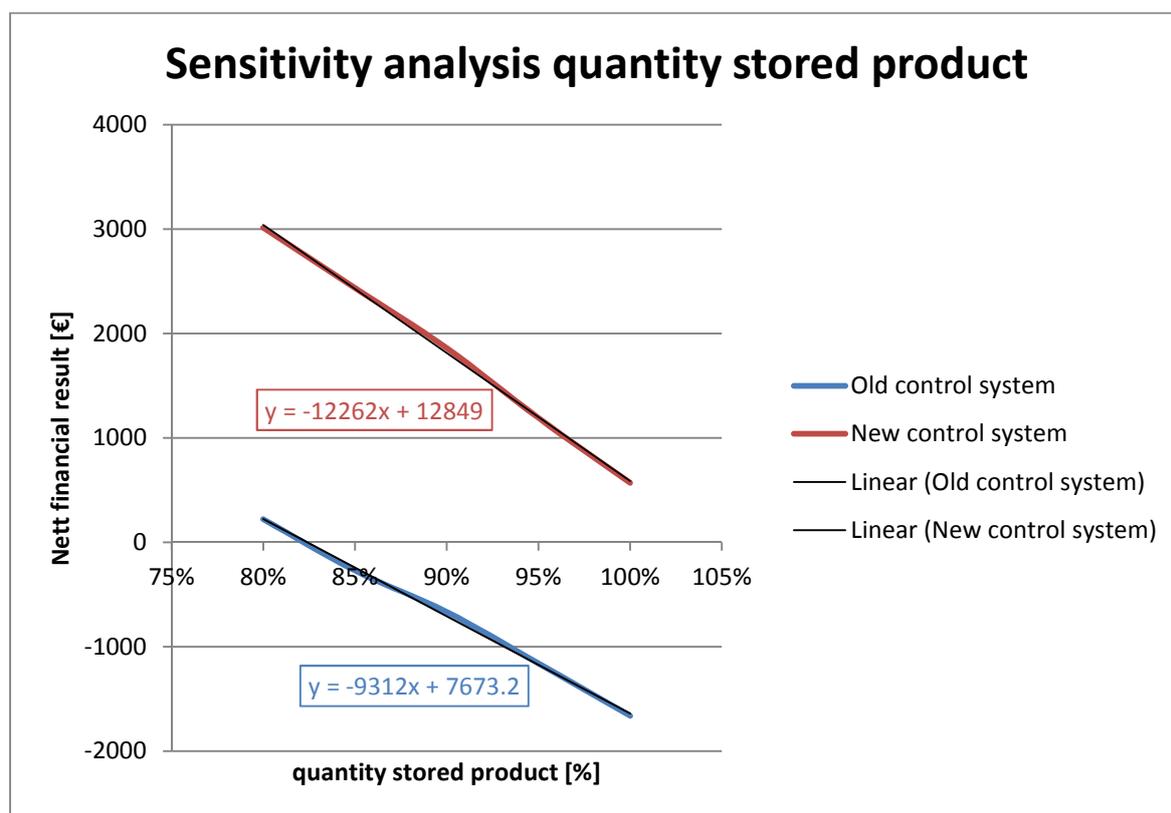


Figure 30 Financial results for both system with different quantity stored product percentage

Figure 30 shows that both systems respond positive on a lower amount of stored product. In both cases the financial result increases when less product is stored. This is expected because less product produces less heat and a smaller amount of product has to be cooled. The regression lines are implemented again. The new control system is more sensitive to a smaller amount of stored product than the old control system. The explanation is that the storage takes more time to reach the maximum allowed temperature because of a lower total energy production. Therefore, the new control system has more time and opportunities to find an appropriate moment to cool already in advance on available solar energy.

6 Discussion

The most important point of discussion relates to the model. A well designed and defined model estimates and indicates possible outputs, but it will always be an approximation of reality. This should be taken into account when the results of this research are considered. As an example the water balance is not taken into account within the model. It is important for a good product quality that the relative humidity is optimal. This relative humidity has not been completely taken into account. However, by keeping the product temperatures constant and adding air at the desired temperatures, the relative humidity will not differ a lot from the perfect conditions but it would be better to take this into account as well.

A second point of discussion is the assumption that the equipment incorporates two options; activated at full capacity or not activated at all. Reality however, is different. As the equipment is continuously variable more advanced control strategies are possible. For further research it would be interesting to incorporate a continuously varying cooling capacity into the model through which optimal control theory can be applied and even better results can be obtained. By doing this, the energy pattern of every equipment will be different and it will be possible to maximize profit even better with respect to instantaneously produced solar energy.

The research is performed assuming that the weather is constant during a full hour. It would be a major improvement if the model includes more real-time data than averages for an hour. The results are that the models perform better in specific circumstances and that the temperatures will be reached better, because cooling or ventilation decisions would be taken in direct reaction to changes in weather conditions.

Finally it is assumed that the ventilated air will have the same temperature as the product after circulation through the product. This probably does not correspond with reality because the air needs some time to rise in temperature. Therefore it would be better to model the temperature profile at product level. This was beyond the scope of this research.

The scenario analysis has already proven that for different weather conditions, like different levels of irradiation, the new control system performs even better. However these different levels of irradiation were only based on the weather data for 2009. It is advisable to use weather data of different years as well, to have more reliable improvements of the system.

Another important factor is the timescale. In the research it is assumed that the storage temperature of the product will be reached immediately after harvest. However, after the products are harvested, the temperature will slowly change from harvest temperature to the low storage temperature. This temperature course however, will vary every year due to different circumstances and product quality. This can take weeks or months. Now it is assumed that this will be reached instantaneously.

The last point worth mentioning is the temperature band. The chosen temperature band used in this research is known from practice and it is proven that this temperature band will have no negative effect on product quality. It is interesting however, for further research to investigate the effect of other temperature bands on the product quality. This is interesting because different temperature bands will result in a different energy consumption and so reflect on the financial result on energy. Therefore it is interesting to investigate the effect of the temperature band on product quality. This knowledge could be exploited through application of optimal control theory.

7 Conclusion

In conclusion it can be stated that far more profit can be gained with solar collector panels by farmers than known up till now. By adjusting control schemes of common used equipment, it is possible to change from a negative financial result on energy towards a positive financial result on energy. The yearly result on energy was €-1663, but after adjustment of the control scheme it was possible to have a nett yearly result of €569. This is an improvement of €2232 by only adjusting the control scheme. This answers the major research question for this thesis regarding the financial benefit when a large energy producer will be connected to an energy consumer. In this research, the energy producer is the solar energy system and the energy consumer is the storage system of the case farm.

This improvement can be achieved by reducing the energy exchange with the grid, by using the produced energy more instantaneously. This financial improvement is the result of two factors. The first factor is that the reduced exchange results in a lower energy costs, because every kilowatt hour delivered to the grid and later returned results in a financial loss. The second factor is that the storage facilities together use less energy over the year. This can be explained by a lower amount of cooling hours with the artificial cooling and more ventilating hours with outside air. Ventilation using outside air requires less energy consumption than artificial cooling. The nett contribution of the old control system is 22.100 kWh. The new control system makes a greater nett contribution, namely 28.100 kWh. This is equal to an increase of 27.1% of energy delivered to the grid. The farm becomes more energy efficient with this new system and this will contribute to the durability of the farm.

With the produced models it was possible to do a lot more interesting calculations. For these calculations some scenario analysis have been performed. Scenario analysis showed that the improvement of the new control system increases when the energy prices rise. The same hold when the irradiation level increases.

All research questions have been considered during this research. The most important general answer with respect to the main research question is, that it is indeed possible to create a link between the solar energy production system and the storage system. It is possible to make better use of produced solar energy when it is used instantaneously. By instantaneous use, it is possible to reduce the energy exchange with the grid and therefore it is possible to save money. For this case farm it was possible to save around €2200 on yearly basis. This can be seen as a major improvement on the financial benefits of the solar collectors which makes the final results very promising. Furthermore, it seems that the investment costs are not very high because there only an adjustment in the software is needed.

8 Recommendations

The outcomes of this research are that promising, that it would be a loss if it ends here. Therefore some recommendations are given for further research to explore more possibilities from such a new control system.

The first recommendation refers to the model itself. It would be interesting when the models are expanded by including some kind of weather prediction. In this thesis only the current level of solar irradiation is taken into account, but not prospective levels. With information about the future weather circumstances, it is possible to achieve even a better result. The model could be expanded otherwise by incorporate an option for implementing a windmill. As found in literature from Hiethaar and Pierik (2004), a lot of farmers own a windmill which makes it interesting to connect the storage to the wind energy production in addition to, or instead of, the solar energy production. Wind can be interesting, because it is present day and night and in large quantities during the winter (storage period). The last recommendation regarding the model is to extend it with the water and CO₂ balance. This will increase realism and usability.

The second recommendation is to do research on the influence of the temperature band on quality of the stored products and the relation between product quality and the financial result. With more knowledge about these relations, it is possible to optimize optimally control temperatures.

The third interesting recommendation is to investigate if it is possible to use this model to determine what the optimal cooling equipment would be for a storage facility. It might be that, instead of two large evaporators, it is more interesting to install four small evaporators for instance. In this way the options for activation of cooling equipment will increase for the new control system. A calculation can be made if the additional costs for more cooling equipment are higher or lower than the additional revenues on energy. Such a calculation can be used to advise a customer for the optimal cooling equipment composition for his specific case.

The last recommendation is to work towards an implementation of the new control system. The first step might be to implement the continuous variable equipment. It would also be very interesting to explore the possibility of creating a link between the solar collector panels and the storage system in a real set-up. Finally it would be interesting to see the realized financial achievement reached with the new control system.

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Appendix

Appendix A: Carrot_celeriac_storage.m

```
function [T_cc] = Carrot_celeriac_storage (T_cc, Solar_irradiation, Tout,
T_un, U, Re, a, fr_cooling_cc, num_eva_cc)
% This function models the actions taken in the Carrot and Celeriac storage
% with respect to outside conditions and ventilation and cooling actions.

% Inputs:
% T_cc [C] Temperature in carrot and celeriac storage
% Solar_irradiation [W/m2] Solar irradiation on specific moment
% Tout [C] Temperature outside
% T_un [C] Temperature unions
% U [W * m^-2 * K^-1] Heat transfer coefficient
% Re [m2 * K * W-1] Thermal resistance
% a [m^2*S^-1]
% fr_cooling_cc [0-1] Fraction of needed cooling power.

% Outputs:
% T_cc [C] New product temperature

%% Total dimensions
Lcb = 30.25; % [m] Total length of the storage
building
Wcb = 15.95; % [m] Total width of the storage
building
Hscb = 7.91; % [m] Height in the side of the
storage
Hmcb = 11.65; % [m] Height in the middle of the
storage building

Vcb = Lcb * Wcb * (0.5*(7.91+11.65)); % [m^3] Total volume of the storage
building

%% Storage specifications
Cub_num_carrot = 810 ; % [#] number of
cubicles with carrots in storage
Cub_num_celeriac = 480; % [#] number of
cubicles with celeriac in storage
Vol_cub = 1.6 * 1.2 * 1.05; % [m^3] Volume per
cubicle
Vps = (Cub_num_carrot + Cub_num_celeriac) * Vol_cub; % [m^3] The volume
of the cubicles.

Vacs = Vcb - Vps; % [m^3] Volume of air in storage

Dens_carrot = 440; % [kg/m-3] Density of bulk storage of carrots
http://www.koudecentraal.nl/documents/Peen.pdf
Heat_prod_carrot = 22; % [W/ton] Heat production per ton at 2 degrees.
http://www.koudecentraal.nl/documents/Peen.pdf
Sh_carrot = 3920; % [J/ kg * K] Specific heat of carrots
```

```

Dens_celeriac = 450;          % [kg/m-3] Density of bulk storage of celeriac
http://www.koudecentraal.nl/documents/handboekkkoudetechniek/2D%20Eigenschap%20van%20te%20bewaren%20producten.pdf
Heat_prod_celeriac = 19;     % [W/ton] Heat production of Celeriac at 2
degrees.
http://www.koudecentraal.nl/documents/handboekkkoudetechniek/2B%20Circulatie%20voud.pdf
Sh_celeriac = 3900;         % [J / kg * K] Specific heat of celeriac

Total_storage_carrots = (Cub_num_carrot * Vol_cub * Dens_carrot) / 1000;
% [tons] Total amount of carrots in storage
Total_storage_celeriac = (Cub_num_celeriac * Vol_cub * Dens_celeriac) /
1000; % [tons] Total amount of celeriac in storage

Heat_prod_carrots_total = Total_storage_carrots * Heat_prod_carrot ;
% [W] total amount of heat production of all the carrots
Heat_prod_celeriac_total = Total_storage_celeriac * Heat_prod_celeriac;
% [W] Total amount of heat production of all the celeriac

Total_heat_production_cc = Heat_prod_carrots_total +
Heat_prod_celeriac_total; % [W]

%% Storage system
Cooling_capacity = 51300;    % [W] Cooling capacity of
one evaporator

%% Heat balance
% Energy in the air start
E_air_cc_start = 1006 * 1.2 * Vacs * T_cc; % [J] Energy content of the
air inside the storage

% Energy in Carrots and Celeriac
E_in_cc_start = ((Total_storage_carrots *1000) * T_cc * Sh_carrot) +
((Total_storage_celeriac * 1000) * T_cc * Sh_celeriac); % [J] Total amount
of energy at the start in carrots and celeriac

% Energy production per hour by carrots and celeriac
E_prod_cc = Total_heat_production_cc * 3600; % [J]

% Heat exchange
% Surface
Surf_cc_wo = Hscb * Lcb + (2 * (2 * ( 0.5 *Wcb * ((Hscb + Hmcb)/2)))); %
[m^2] Surface walls outside carrot and celeriac storage
Surf_cc_wi = Hscb * Lcb ; %
[m^2] Heat exchanging surface with union storage
Surf_cc_roof = sqrt((0.5*Wcb)^2 + (Hmcb - Hscb)^2) * Lcb * 2; %
[m^2] Heat exchanging surface roof carrot and celeriac storage

% Transfer
E_tr_cc = U * Surf_cc_wo * (T_cc - Tout) + U * Surf_cc_wi * (T_cc - T_un) *
3600; % [J] heat exchange through walls according to formula 7 from FTE-
25303

E_roof_cc = U * Surf_cc_roof * (T_cc - (Tout + Re * a *
Solar_irradiation))*3600; % [J] energy through roof due to external
temperature and solar irradiation

```

```
E_tr_total_cc = E_tr_cc + E_roof_cc ;
% [J] Total energy transfer trough roofs and walls

% Cooling
E_cooled_extracted_cc = fr_cooling_cc * num_eva_cc * Cooling_capacity
*3600; % [J] Energy taken away with cooling installation (nog een hoop
voor in te vullen, vermogen en die fractie ook nog maken)

% Conditions carrots and celeriac end
E_in_cc_end = E_air_cc_start + E_in_cc_start + E_prod_cc - E_tr_total_cc
- E_cooled_extracted_cc; % [J] New
total energy in carrots and celeriac (assumed that the air keeps the same
temperature and relative humidity and that the energy taken away by the
cooling is coming directly from the carrots and celeriac)
T_cc = E_in_cc_end / (((Total_storage_carrots *1000) * Sh_carrot) +
((Total_storage_celeriac * 1000) * Sh_celeriac)+(1006*1.2*Vacs)); % [C]
new temperature of the carrots and celeriac
```

Appendix B: Seed_potato_storage.m

```
function [T_po] = Seed_potato_storage(T_po, Solar_irradiation, Tout, U, Re,
a, Fan_nr_po, fr_vent_out_po, E_air_out, fr_cooling_po)
% This function models the actions taken in the seed potato storage
% with respect to outside conditions and ventilation and cooling actions.

% Inputs:
% T_po [C] Temperature in seed potato storage
% Solar_irradiation [W/m^2] Solar irradiation on specific moment
% Tout [C] Temperature outside
% U [W * m^-2 * K^-1] Heat transfer coefficient
% Re [m^2 * K * W^-1] Thermal resistance
% a [m^2*S^-1]
% Fan_nr_po [#] Number of fans activated
% fr_vent_out_po [0-1] Fraction of ventilation flow from outside
% E_air_out [J] Energy in the outside air
% fr_cooling_po [0-1] Fraction of needed cooling power.

% Outputs:
% T_po [C] New product temperature

%% Total dimensions
Lpb = 13.30; % [m] Length of the potato storage
building
Wpb = 14.65; % [m] Width of the potato storage
building
Hpbs = 8.32; % [m] Height of the potato storage
building on the side
Hpbm = 10.33; % [m] Height of the potato storage
building in the middle

Vpb = Lpb * Wpb * 0.5*(Hpbs + Hpbm); % [m^3] Volume of the potato
storage building

%% Heat exchanging surface

Surf_p_wo = 2*(Hpbs * Lpb) + (2 *(2 * ( 0.5 *Wpb * ((Hpbs + Hpbm)/2) ));
% [m^2] Surface walls outside potato storage
Surf_p_roof = sqrt((0.5*Wpb)^2 + (Hpbm - Hpbs)^2) * Lpb * 2;
% [m^2] Heat exchanging surface roof potato storage

%% storage specifications
Cub_num_p = 450; % [#] The
amount of cubicles stored
Vol_cub = 1.6 * 1.2 * 1.05; % [m^3]
Volume per cubicle
Vps = Cub_num_p * Vol_cub; % [m^3] The
volume of the cubicles.

Vaps = Vpb - Vps; % [m^3]
Volume of air in the potato storage

Fan_capacity_po = 26000; % [m^3*h^-
1] Blown air per fan
```

```

Cooling_power_po = 40000; % [W]
Cooling power when mechanised cooling is on.

Dens_pot = 650; % [kg/m^-3]
Density of potatoes
http://www.koudecentraal.nl/documents/handboekkoude techniek/2B%20Circulatie%20voud.pdf
Sh_potato = 3670; % [J / kg *
K] Specific heat of potatoes

Kg_cubicle = Vol_cub * Dens_pot;

Total_storage_potato = (Kg_cubicle * Cub_num_p) / 1000; % [ton]
total amount of potatoes in storage

Heat_prod_pot = 12; % [W/ton]
heat production potatoes at 5 degrees
Total_heat_prod_pot = Total_storage_potato * Heat_prod_pot; % [W] Total
heat production from the potatoes

%% Heat balance

% Energy air start
E_air_po_start = 1.2 * Vaps * 1006 * T_po;
% [J] Energy content of the air inside the storage

% Energy in seed potatoes
E_in_po_start = Sh_potato * (Total_storage_potato * 1000) * T_po;
% [J] Amount of energy stored in the potatoes

% Energy production per hour by potatoes
E_prod_po = Total_heat_prod_pot * 3600;
% [J] Total energy production from the potatoes

% Heat exchange
E_tr_po = U * Surf_p_wo * (T_po - Tout) * 3600;
% [J] heat exchange through walls according to formula 7 from FTE-25303

E_roof_po = U * Surf_p_roof * (T_po - (Tout + Re * a *
Solar_irradiation))*3600; % [J] energy through roof due to external
temperature and solar irradiation

E_tr_total_po = E_tr_po + E_roof_po ;
% [J] Total energy transfer trough roofs and walls

% Heat flow trough ventilation
diff_energy_air = E_air_out - (E_air_po_start/Vaps);
% [J/m3] Energy nett difference per cubic meter of air between inside and
outside
E_vent_netto_po = Fan_capacity_po * Fan_nr_po * fr_vent_out_po *
diff_energy_air; % [J] Energy nett flow

% Energy taken away with cooling installation

```

```
E_cooled_extracted_po = (Cooling_power_po*3600) * fr_cooling_po;
% [J] Energy taken away with cooling installation (nog een hoop voor in te
vullen, vermogen en die fractie ook nog maken)

% Energy in Potatoes end
E_in_po_end = E_air_po_start + E_in_po_start + E_prod_po - E_tr_total_po +
E_vent_netto_po - E_cooled_extracted_po;      % [J] New total energy in
potatoes
T_po = E_in_po_end / ((Sh_potato * (Total_storage_potato
*1000))+(1.2*Vaps*1006));                    % [C] New
temperature of the potatoes
```

Appendix C: Union_storage.m

```

function [T_un] = Union_storage(T_un, Solar_irradiation, Tout, T_cc,U, Re,
a, Fan_nr_un, fr_vent_out_un, E_air_out, fr_cooling_un, num_eva_un)
% This function models the actions taken in the seed potato storage
% with respect to outside conditions and ventilation and cooling actions.

% Inputs:
% T_un           [C] Temperature in union storage
% Solar_irradiation [W/m2] Solar irradiation on specific moment
% Tout          [C] Temperature outside
% T_cc          [C] Temperature carrots and celeriac
% U             [W * m^-2 * K^-1] Heat transfer coefficient
% Re           [m2 * K * W-1] Thermal resistance
% a            [m^2*S^-1]
% Vent_un      [m3/h] Ventilation flow
% fr_vent_out_un [0-1] Fraction of ventilation flow from outside
% E_air_out    [J] Energy in the outside air
% x_out        [g/kg] Humidity of outside air
% fr_cooling_un [0-1] Fraction of needed cooling power.

% Outputs:
% T_un         [C] New product temperature
%% Total dimensions

Lub = 30.25;           % [m] Length union storage building
Wub = 14.65;          % [m] Width union storage building
Husb = 7.91;          % [m] Height side storage building
Humb = 10.33;         % [m] Height middle of the storage
building

Vub = Lub * Wub * 0.5 * (Husb+ Humb); % [m^3] Volume union storage
building

%% Heat exchanging surface

Surf_u_wo = Husb * Lub + (2 * (2 * ( 0.5 *Wub * ((Husb + Humb)/2))))); %
[m^2] Surface walls outside union storage
Surf_u_wi = Husb * Lub ; %
[m^2] Heat exchanging surface with carrot storage
Surf_u_roof = sqrt((0.5*Wub)^2 + (Humb - Husb)^2) * Lub * 2; %
[m^2] Heat exchanging surface roof union storage

%% Storage area dimensions
Lus = 29.78;           % [m] Length union
storage building
Wus = 13.00;           % [m] Width union
storage building
Hus = 4.25;            % [m] Height union
storage

Fan_capacity = 15150; % [m^3*h-1] Ventilation
capacity per fan
Cooling_power_un = 34600; % [W] Capacity of the
mechanized cooling
Eva_number_un = num_eva_un; % [#] Number of
evaporators

```

```

Ch_r = (1 + 0.41 ) / 2; % [m] Ventilation
channels average radius
Ch_l = 13.50; % [m] Ventilation
channel length
Ch_num = 8; % [#] Amount of
ventilation channels
Ch_vol = (pi * (Ch_r ^ 2)) / 2 * Ch_l * Ch_num; % [m^3] Channels volume

Vus = (Lus * Wus * Hus) - Ch_vol; % [m^3] Volume actual
union storage
Vaus = Vub - Vus; % [m^3] Volume of air in
the union storage [m-3]

%% Unions in storage

Dens_union = 550; % Density
of unions [kg/m-3]
http://www.koudecentraal.nl/documents/handboekoudetechniek/2B%20Circulatievoud.pdf
Sh_union = 3780; % Specific
heat of unions [J/(kg*K)] http://www.koudecentraal.nl/documents/Sjalot.pdf

Total_storage_union = (Vus * Dens_union) / 1000; % [ton]
total tons of unions in the storage

Heat_prod_union = 13; % [W/ton]
heat production of unions at 2 C
http://www.koudecentraal.nl/documents/handboekoudetechniek/2B%20Circulatievoud.pdf

Total_heat_prod_union = Total_storage_union * Heat_prod_union; % [W]

%% Heat balance

% Energy air start
E_air_un_start = Vaus * 1.2 * 1006 * T_un;
% [J]Energy in the air inside the storage

% Energy start in unions
E_in_un_start = Sh_union * (Total_storage_union * 1000) * T_un;
% [J] Amount of energy stored in the unions

% Energy production per hour by unions
E_prod_un = Total_heat_prod_union * 3600; % [J]

% Transfer
E_tr_un = U * Surf_u_wo * (T_un - Tout) + U * Surf_u_wi * (T_un - T_cc) *
3600; % [J] heat exchange through walls according to formula 7 from
FTE-25303

E_roof_un = U * Surf_u_roof * (T_un - (Tout + Re * a *
Solar_irradiation))*3600; % [J] energy through roof due to external
temperature and solar irradiation

```

```
E_tr_total_un = E_tr_un + E_roof_un;
% [J] Total energy transfer trough roofs and walls

% Heat flow trough ventilation
diff_energy_air = E_air_out - (E_air_un_start/Vaus);
% [J/m^3] Difference in energy between inside and outside air
E_vent_netto_un = Fan_capacity * Fan_nr_un * fr_vent_out_un *
diff_energy_air; % [J] Energy flow through ventilation from inside to
outside or vice versa

% Energy taken away with cooling installation
E_cooled_extracted_un = (Cooling_power_un*Eva_number_un*3600) *
fr_cooling_un; % [J] Energy taken away with cooling installation (nog
een hoop voor in te vullen, vermogen en die fractie ook nog maken)

% Conditions unions end
E_in_un_end = E_air_un_start + E_in_un_start + E_prod_un - E_tr_total_un +
E_vent_netto_un - E_cooled_extracted_un; % [J] New total energy in
unions
T_un = E_in_un_end/(((Total_storage_union * 1000) * Sh_union)+(Vaus * 1.2
*1006)); % [C] New union temperature
```

Appendix D: Weather_data.m

```

function [Tout, RH, Solar_irradiation_direct, Solar_irradiation_diffuse,
Day_nr, Day_time, Ptot] = Weather_data()
load data_CAB_2009
load dataT_CAB_2009

a=1;           % help parameter
b=60;         % help parameter

Data=[];      % New data matrix

for j=1:365           % loop for all the days
of a year
    a=1;             % reset of the help
parameter
    b=60;           % reset of the help
parameter
    for i=1:24       % loop for all the
hours of a day
        Tout=sum(Dataset_T(a:b, j,1))/(b-a); % [degrees] Average
outside temperature for a hour.
        RH=sum(Dataset_T(a:b, j, 2))/(b-a); % [%] Average relative
humidity for an hour
        Ptot=sum(Dataset_T(a:b, j,3)*100)/(b-a); % [Pa] Average outside
air pressure
        Solar_irradiation_direct=sum(Dataset(a:b, j, 2))/(b-a); %
[W/m2] Average direct solar irradiation per hour
        Solar_irradiation_diffuse=sum(Dataset(a:b, j, 3))/(b-a); %
[W/m2] Average diffuse solar irradiation per hour
        rule_number = (j-1)*24+i; % Help for making the
matrix to determine the rule number
        Data(rule_number,1:7)= [j, i, Tout,RH, Ptot,
Solar_irradiation_direct, Solar_irradiation_diffuse]; % making the new rule
with data in the matrix
        a= a+60; % help parameter is set
60 minutes/ 1 hour higher
        b= b+60; % help parameter is set
60 minutes/ 1 hour higher
    end
end

A=Data(5113:8760, 3:7);
B=Data(1:5112, 3:7);
C=Data(1:8760, 1:2);
D=[A;B];
Data=[C,D];

Day_nr = Data(1:8760,1); % Day number is gained from the
matrix
Day_time=Data(1:8760,2); % Day time is gained from the
matrix
Tout=Data(1:8760,3); % Outside temperature is gained
from the matrix
RH=Data(1:8760,4); % Relative humidity is gained
from the matrix

```

```
Ptot=Data(1:8760,5);           % Air pressure is gained from  
the matrix  
Solar_irradiation_direct=Data(1:8760,6); % Direct solar irradiation is  
gained from the matrix  
Solar_irradiation_diffuse=Data(1:8760,7); % Diffuse solar irradiation is  
gained from the matrix
```

Appendix E: Solar_collectors.m

```
function [Energy_prod] =
Solar_collectors(Solar_irradiation_direct,Solar_irradiation_diffuse,
Day_time, Day_nr)
    % This function calculates the amount of electric energy is produced on
    % a certain moment by the solar collectors.

    % Inputs:
        % Solar irradiation on every moment          [W/m2]
        % Hour on the day 1-24                        [h]
        % Day number of the year 1-365

    % Outputs:
        % Produced energy by the solar collectors     [W]
%%
Efficiency_solar_collector = 0.215;
% 21.5 % irradiation turned into electric energy

%% Elevation angle calculation
u = 15 * Day_time;
% [h] Hour angle calculation

d = 23.45 * sind(360*((284+Day_nr)/365));
% [degrees] Suns declination

latitude_nl = 52;
% [degrees] Latitude in the Netherlands

hs = asind((sind(latitude_nl)*sind(d))-
(cosd(latitude_nl)*cosd(d)*cosd(u)));% [degrees] Elevation angle of the sun
at solar time

as = asind((cosd(d)*sind(u))/cosd(hs));
% [degrees] Azimuth angle of the sun at solar time t(h)

if Day_time >= 12
    as = -1*as;
else
    as = as;
end

%% Irradiation intensity of the sun on a surface calculation

if Solar_irradiation_diffuse <=0;
    Solar_irradiation_diffuse = 0;
else
    Solar_irradiation_diffuse = Solar_irradiation_diffuse;
end

% surface 1
azimuth_angle_1 = 30;           % [degrees]
slope_1 = 35;                   % [degrees] roof slope

hp_1= 90-slope_1;               % [degrees]
```

```

angle_irradiation_1 = cosd(hs)*cosd(hp_1)*cosd(as-
azimuth_angle_1)+sind(hs)*sin(hp_1); % [degrees] angle of irradiation on
plane 1

irradiation_intensity_1 = Solar_irradiation_direct *
angle_irradiation_1+Solar_irradiation_diffuse; %
[W/m2] Irradiation intensity of the sun on surface 1

Surf_1 = 165 * (1.65 * 0.99); % [m^2] the surface of solar
collectors

Energy_prod_1=irradiation_intensity_1 * Efficiency_solar_collector *
Surf_1; % [W] Produced energy by plane 1

if Energy_prod_1 <= 400;
    Energy_prod_1 = 0;
else
    Energy_prod_1 = Energy_prod_1;
end

% surface 2
azimuth_angle_2 = -60; % [degrees]
slope_2 = 25; % [degrees] roof slope

hp_2= 90-slope_2; % [degrees]

angle_irradiation_2 = cosd(hs)*cosd(hp_2)*cosd(as-
azimuth_angle_2)+sind(hs)*sind(hp_2); % [degrees] angle of irradiation on
plane 2

irradiation_intensity_2 = Solar_irradiation_direct *
angle_irradiation_2+Solar_irradiation_diffuse; %
[W/m2] Irradiation intensity of the sun on surface 2

Surf_2 = 110 * (1.65 * 0.99); % [m^2] the surface of solar
collectors

Energy_prod_2=irradiation_intensity_2 * Efficiency_solar_collector *
Surf_2; % [W] Produced energy by plane 2

if Energy_prod_2 <= 400;
    Energy_prod_2 = 0;
else
    Energy_prod_2 = Energy_prod_2;
end

% surface 3
azimuth_angle_3 = 30; % [degrees]
slope_3 = 30; % [degrees] roof slope

hp_3= 90-slope_3; % [degrees]

```

```
angle_irradiation_3 = cosd(hs)*cosd(hp_3)*cosd(as-
azimuth_angle_3)+sind(hs)*sind(hp_3); % [degrees] angle of irradiation on
plane 3

irradiation_intensity_3 = Solar_irradiation_direct *
angle_irradiation_3+Solar_irradiation_diffuse; %
[W/m2] Irradiation intensity of the sun on surface 3

Surf_3 = 96 * (1.65 * 0.99); % [m^2] the surface of solar
collectors

Energy_prod_3=irradiation_intensity_3 * Efficiency_solar_collector *
Surf_3; % [W] Produced energy by plane 1

if Energy_prod_3 <= 400;
    Energy_prod_3 = 0;
else
    Energy_prod_3 = Energy_prod_3;
end

%% Total production

Energy_prod = (Energy_prod_1 + Energy_prod_2 + Energy_prod_3)*3600;
% [J/h] Total produced energy by plane 1, 2 and 3.
```

Appendix F: Main_screen.m

```
%% Main screen
% This is the virtual world. This is the place where all the programs run
% and give their result to.
close all
clc
clear all
format compact

%% Which calculation
% With this system, both the original case can be calculated and the new
% case can be calculated with respect to the solar energy production. Put a
% 0 if you want to calculate the original case. a 1 for the new case.

Calculation_case = 1;           % 0 = old case, 1 is new case
%%

[Tout, RH, Solar_irradiation_direct, Solar_irradiation_diffuse, Day_nr,
Day_time, Ptot] = Weather_data(); % Get the weather data from the
matrix

T_cc = 1.0; % [C] Initial temperature carrots and celeriac storage
T_un = 4.5; % [C] Initial temperature union storage
T_po = 4.0; % [C] Initial temperature potato storage

Rc = 4.85; % [m^2 * K * W^-1] Thermal resistance walls and roof
U = 1/Rc; % [W * m^-2 * K^-1] Effective heat transfer coefficient

Re = 0.04; % [m^2 * K * W^-1] (formula sheet FTE-25303 page 2)
a = 0.9; % [m^2*S^-1] (formula sheet FTE-25303 page 2)

% Initial status of all the cooling/ventilation equipment
% They are all switched off at the beginning
fr_vent_out_un = 0;
fr_cooling_un = 0;
Fan_nr_un=0;
fr_vent_out_po = 0;
fr_cooling_po = 0;
Fan_nr_po=0;
fr_cooling_cc=0;
num_eva_cc = 0;
num_eva_un=0;

% Vector pre-programming for easy fit in later
kWh_production=1:8760;
T_cc_vector=1:8760;
T_po_vector=1:8760;
T_un_vector=1:8760;
E = 0;
F = 0;
G = 0;
H = 0;
I = 0;
kWh_energy_result =1:8760;
Energy_consumption_from_grid = 0; % Needed for the stepwise energy
tax payment over all energy taken from the grid
```

```

Energy_production_solar_collectors =0; % Needed because not more than
91.000 kWh will be subsidized, so above this limit, the energy will not be
subsidized.
Financial_result = 1:8760; % Financial result start at the
first of september

%% Money from SDE subsidy
SDE_per_kWh = 0.056;
%[€/kWh] subsidy per produced kWh

%% Money from exchange with the grid
result_per_kWh = 0.11-SDE_per_kWh;
%[€/kWh] Price paid by the energy company for the produced energy when it
enters the grid
costs_per_kWh = 0.104;
%[€/kWh] Price paid by the farmer for every kWh he consumes from the grid

for i = 1:length(Tout) % Iteration for every hour of the year,
starting at the first of september till the end of august

    E_air_out = 1.2 * 1006 * Tout(i); % Calculating the energy content of
the outside air

    %% Empty storage facilities
    % When the storage facilities will be empty, the temperature will be
set below
    % the minimum value and the cooling and ventilation systems will do
nothing.

    if i >=5808; % If it is after the first of may, then potato storage
is empty
        T_po = 3.5;
    else
    end

    if i <= 1464 || i>=6168; % If it is before the first of november or
after the 15th of may, then carrot and celeriac storage is empty
        T_cc = 0.5;
    else
    end

    if i>=6552; % If it is after the first of june, the onion storage is
empty
        T_un = 3.5;
    else
    end

    %% Energy calculations and financial result of it
    [Energy_prod] =
Solar_collectors(Solar_irradiation_direct(i),Solar_irradiation_diffuse(i),
Day_time(i), Day_nr(i)); %[J] Energy production of the iterated hour
    Energy_production_solar_collectors = Energy_production_solar_collectors
+ (Energy_prod/3600000); % [kWh] Counter for maximum produced energy
    if Energy_production_solar_collectors >= 91000
% Above this value, no more subsidy

```

```

    SDE_per_kWh =0;
% [€] So subsidy is set to zero
    end
    SDE_subsidy = (Energy_prod/3600000)*SDE_per_kWh;
% [€] calculating the subsidy amount over the produced energy

    if Calculation_case == 0;
        [Fan_nr_un, Fan_nr_po, fr_vent_out_un, fr_vent_out_po,
fr_cooling_un, fr_cooling_po, fr_cooling_cc, num_eva_cc, num_eva_un,
Energy_result] = Control_system_old_case (Energy_prod, Tout(i), T_un, T_po,
T_cc, Fan_nr_un, fr_cooling_un, fr_vent_out_un, fr_vent_out_po,
fr_cooling_po,Fan_nr_po, fr_cooling_cc, num_eva_cc, num_eva_un);
    elseif Calculation_case == 1;
        [Fan_nr_un, Fan_nr_po, fr_vent_out_un, fr_vent_out_po,
fr_cooling_un, fr_cooling_po, fr_cooling_cc, num_eva_cc, num_eva_un,
Energy_result] = Control_system_new_case (Energy_prod, Tout(i), T_un, T_po,
T_cc, Fan_nr_un, fr_cooling_un, fr_vent_out_un, fr_vent_out_po,
fr_cooling_po,Fan_nr_po, fr_cooling_cc, num_eva_cc, num_eva_un);
    end

    if Energy_result <= 0
% If the energy result is smaller than 0, extra energy should be taken from
the grid
        Energy_consumption_from_grid = Energy_consumption_from_grid + (-1 *
(Energy_result/3600000)); % [kWh] Counter for how much energy has been
taken from the grid over the year for energy tax calculation
        if Energy_consumption_from_grid <= 10000
% First energy consumption step is from 0 till 10.000 kWh
            Energy_tax = 0.1462;
% [€] Energy tax for the first step between 0 till 10.000 kWh
        elseif Energy_consumption_from_grid <= 50000 &&
Energy_consumption_from_grid >= 10001; % Second energy consumption
step is from 10.001 till 50.000 kWh
            Energy_tax = 0.0555;
% [€] Energy tax for the second step between 10.001 till 50.000 kWh
        else
% Above 50.000 kWh the third energy consumption step holds
            Energy_tax = 0.0147;
% [€] Energy tax for the last step, above 50.000 kWh
        end
        financial_result_loop =
(Energy_result/3600000)*(costs_per_kWh+Energy_tax); %
[€] Costs of energy
    else
% If the energy result is larger than 0, the rest energy can be sold to the
grid
        financial_result_loop = (Energy_result/3600000) * result_per_kWh;
% [€] Benefits of energy
    end
    Financial_result(i) = financial_result_loop + SDE_subsidy;
% [€] Financial result so far from the energy production and exchange with
the grid

    %% Storage temperatures calculations

```

```

    [T_cc] = Carrot_celeriac_storage (T_cc, Solar_irradiation_direct(i),
    Tout(i), T_un, U, Re, a, fr_cooling_cc, num_eva_cc); % Calculating the
    new carrot and celeriac temperature
    [T_po] = Seed_potato_storage(T_po, Solar_irradiation_direct(i),
    Tout(i), U, Re, a, Fan_nr_po, fr_vent_out_po, E_air_out, fr_cooling_po); %
    Calculating the new potato temperature
    [T_un] = Union_storage(T_un, Solar_irradiation_direct(i), Tout(i),
    T_cc, U, Re, a, Fan_nr_un, fr_vent_out_un, E_air_out, fr_cooling_un,
    num_eva_un); % Calculating the new union temperature
    %% Vector making for results and figures
    kWh_production(i)=Energy_prod/3600000; % [kWh] Energy production
    transformed into kWh
    T_cc_vector(i)= T_cc; % Adding then new temperature
    to the year vector
    T_po_vector(i)= T_po;
    T_un_vector(i)= T_un;
    kWh_energy_result(i)= Energy_result/3600000; % Calculating the net
    energy flow

    if Fan_nr_po >=1
        Fan_nr_po_calc = 1;
    else
        Fan_nr_po_calc =0;
    end

    if Fan_nr_un >=1
        Fan_nr_un_calc = 1;
    else
        Fan_nr_un_calc =0;
    end
    E = E + fr_cooling_cc;
    F = F + fr_cooling_un;
    G = G + fr_cooling_po;
    H = H + Fan_nr_po_calc;
    I = I + Fan_nr_un_calc;
end

Financial_result_end = cumsum(Financial_result);
Financial_result_end(end)

figure(1)
plot(Day_nr, cumsum(kWh_production))
title('Cumulative energy production through the year')
xlabel('Day nr')
ylabel('Energy production [kWh]')

figure(2)
plot(Day_nr, T_cc_vector)
title('Carrot and celeriac storage temperature')
xlabel('Day nr')
ylabel('Temperature [C]')

figure(3)
plot(Day_nr, T_po_vector)
title('Potato storage temperature')
xlabel('Day nr')
ylabel('Temperature [C]')

```

```
figure(4)
plot(Day_nr, T_un_vector)
title('Union storage temperature')
xlabel('Day nr')
ylabel('Temperature [C]')
```

```
figure(5)
plot(Day_nr, cumsum(kWh_energy_result))
title('Cumulative energy exchange through the year')
xlabel('Day nr')
ylabel('cumulative energy production - consumption [kWh]')
```

```
figure(6)
plot(Day_nr, cumsum(Financial_result))
title('Cumulative financial result over the year')
xlabel('Day nr')
ylabel('result [€]')
```

Appendix G: Control_system_old_case.m

```
function [Fan_nr_un, Fan_nr_po, fr_vent_out_un, fr_vent_out_po,
fr_cooling_un, fr_cooling_po, fr_cooling_cc, num_eva_cc, num_eva_un,
Energy_result] = Control_system_old_case (Energy_prod, Tout, T_un, T_po,
T_cc, Fan_nr_un, fr_cooling_un, fr_vent_out_un, fr_vent_out_po,
fr_cooling_po, Fan_nr_po, fr_cooling_cc, num_eva_cc, num_eva_un)
% This function takes the product temperatures and the produced energy into
% account and makes decisions about which cooling and ventilation
% equipment should be switched on.

% Inputs:
% Energy_prod      [J/h] Produced energy by the solar collectors
% Tout             [C] Temperature outside
% T_un             [C] Temperature in union storage
% T_po            [C] Temperature in potato storage
% T_cc            [C] Temperature carrots and celeriac
% Fan_nr_un       [#] Number of switched on Fans in the union storage
% fr_cooling_un   [0/1] Union cooling on/off
% fr_vent_out_un  [0-1] Fraction of outside air union ventilation
% fr_vent_out_po  [0-1] Fraction of outside air potato ventilation
% fr_cooling_po   [0/1] Potato cooling on/off
% Fan_nr_po       [#] Number of switched on Fans in the potato
storage
% fr_cooling_cc   [0/1] Carrot and celeriac cooling on/off
% num_eva_cc      [#] Number of switched on evaporators cc storage
% num_eva_un      [#] Number of switched on evaporators union storage

% Outputs:
% Fan_nr_un       [#] Number of switched on Fans in the union storage
% Fan_nr_po       [#] Number of switched on Fans in the potato
storage
% fr_vent_out_un  [0-1] Fraction of outside air union ventilation
% fr_vent_out_po  [0-1] Fraction of outside air potato ventilation
% fr_cooling_un   [0/1] Union cooling on/off
% fr_cooling_po   [0/1] Potato cooling on/off
% fr_cooling_cc   [0/1] Carrot and celeriac cooling on/off
% num_eva_cc      [#] Number of switched on evaporators cc storage
% num_eva_un      [#] Number of switched on evaporators union storage
% Energy_result   [J/h] Energy netto flow at the end

%% Setpoints Settings

%Unions
T_un_set = 4.5;           % [C] Setpoint temperature of unions
T_un_dev = 0.3;          % [C] Maximum deviation from setpoint

T_un_lb = T_un_set - T_un_dev; % [C] Union temperature under bound
T_un_ub = T_un_set + T_un_dev; % [C] Union temperature upper bound

% Seed potatoes
T_po_set = 4.0;          % [C] Setpoint temperature of the seed
potatoes
T_po_dev = 0.3;          % [C] Maximum deviation from setpoint
```

```

T_po_lb = T_po_set - T_po_dev;      % [C] Seed potato temperature under
bound
T_po_ub = T_po_set + T_po_dev;      % [C] Seed Potato temperature upper
bound

% Carrots and Celeriac
T_cc_set = 1.0;                    % [C] Setpoint temperature of carrots
and celeriac
T_cc_dev = 0.1;                    % [C] Maximum deviation from setpoint

T_cc_lb = T_cc_set - T_cc_dev;      % [C] C&C temperature under bound
T_cc_ub = T_cc_set + T_cc_dev;      % [C] C&C temperature upper bound

%% Reset

if Tout >= T_un_lb && Tout<= T_un_ub      % If the outside
temperature is between the temperature boundaries
    if fr_vent_out_un >= 0.01 && fr_cooling_un == 0      % If the storage is
cooled with outside air
        fr_vent_out_un = 0;                                % Stop cooling with
outside air
        Fan_nr_un = 0;                                    % Switch off the
fans
        fr_cooling_un = 0;                                % Make sure the
cooling is off as well
        num_eva_un = 0;                                    % Also make sure
the evaporators are off
    end
end

if Tout >= T_po_lb && Tout<= T_po_ub      % If the outside
temperature is between the temperature boundaries
    if fr_vent_out_po >= 0.01 && fr_cooling_po == 0      % If the storage is
cooled with outside air
        fr_vent_out_po = 0;                                % Stop cooling with
outside air
        Fan_nr_po = 0;                                    % Switch off the
fans
        fr_cooling_po = 0;                                % Make sure the
cooling is off as well
    end
end
%% Necessarry cooling

% Unions
if T_un >= T_un_ub ;                    % In case the union
temperature is higher than the maximum allowed temperature, necessary
action is needed
    Fan_nr_un=8;                                % When necessary
action is needed, all the fans will be switched on.
    if T_un >= Tout                        % When the union
temperature is higher than the outside temperature, it is possible to cool
with outside air
        fr_vent_out_un = (T_un_lb-T_un)/(Tout-T_un);    % [0-1] fraction
outside air for ventilation to get the right ventilation temperature
        if fr_vent_out_un >=1;            % Cannot be more
than 1 or 100% outside air

```

```

        fr_vent_out_un = 1;
    else
    end
    fr_cooling_un = 0;           % Artificial cooling is off when cooled
with outside air
    num_eva_un =0;             % Evaporators are off when cooled with
outside air
    else
        fr_vent_out_un = 0;     % if outside air is higher than inside
air, don't ventilate with outside air
        fr_cooling_un =1;       % Artificial cooling is switched on
        num_eva_un=2;           % Both 2 evaporators are switched on
    end
elseif T_un<=T_un_lb;         % If the union temperature is lower
than the lower bound temperature, switch off all
    fr_cooling_un = 0;
    fr_vent_out_un = 0;
    Fan_nr_un=0;
    num_eva_un=0;

end

% Seed potatoes
if T_po >= T_po_ub           % In case the
potato temperature is higher than the maximum allowed temperature,
necessary action is needed
    Fan_nr_po=2;             % When necessary
action is needed, all the fans will be switched on.
    if T_po >= Tout           % When the potato
temperature is higher than the outside temperature, it is possible to cool
with outside air
        fr_vent_out_po = (T_po_lb-T_po)/(Tout-T_po); % [0-1] fraction
outside air for ventilation to get the right ventilation temperature
        if fr_vent_out_po >=1; % Cannot be more
than 1 or 100% outside air
            fr_vent_out_po = 1;
        else
        end
        fr_cooling_po = 0;     % Artificial cooling is off
    else
        fr_vent_out_po = 0;     % if outside air is higher than inside
air, don't ventilate with outside air
        fr_cooling_po =1;       % Artificial cooling is switched on
    end
elseif T_po<=T_po_lb;       % If the potato temperature is lower
than the lower bound temperature, switch off all
    fr_vent_out_po = 0;
    fr_cooling_po = 0;
    Fan_nr_po=0;
end

% Carrots and Celeriac
if T_cc >= T_cc_ub           % If T_cc exceeds the maximum
temperature, necessary cooling action is needed
    fr_cooling_cc = 1;         % [0-1] 0 = off, 1 = on.
    num_eva_cc = 3;           % number of switched on evaporators

```

```
elseif T_cc<=T_cc_lb;           % If T_cc goes below the minimum
temperature, switch off all the cooling.
    fr_cooling_cc=0;
    num_eva_cc = 0;
end

%% extra additions
%% Conversion
Energy_prod_watts_start = Energy_prod / 3600;           % [W]
Transform the energy production of the hour towards Watts

Energy_prod_watts = Energy_prod_watts_start - (Fan_nr_un * 2957 +
fr_cooling_un * ((34600*num_eva_un)/4))- (num_eva_cc * 51300/4)- (Fan_nr_po
* 1651 + fr_cooling_po * (40000/4)); % Energy left after the necessary
cooling

Energy_result = Energy_prod_watts*3600; %[J/h]
```

Appendix H: Control_system_new_case.m

```
function [Fan_nr_un, Fan_nr_po, fr_vent_out_un, fr_vent_out_po,
fr_cooling_un, fr_cooling_po, fr_cooling_cc, num_eva_cc, num_eva_un,
Energy_result] = Control_system_new_case (Energy_prod, Tout, T_un, T_po,
T_cc, Fan_nr_un, fr_cooling_un, fr_vent_out_un, fr_vent_out_po,
fr_cooling_po, Fan_nr_po, fr_cooling_cc, num_eva_cc, num_eva_un)
% This function takes the product temperatures and the produced energy into
% account and makes decisions about which cooling and ventilation
% equipment should be switched on.

% Inputs:
% Energy_prod      [J/h] Produced energy by the solar collectors
% Tout             [C] Temperature outside
% T_un             [C] Temperature in union storage
% T_po             [C] Temperature in potato storage
% T_cc             [C] Temperature carrots and celeriac
% Fan_nr_un       [#] Number of switched on Fans in the union storage
% fr_cooling_un   [0/1] Union cooling on/off
% fr_vent_out_un  [0-1] Fraction of outside air union ventilation
% fr_vent_out_po  [0-1] Fraction of outside air potato ventilation
% fr_cooling_po   [0/1] Potato cooling on/off
% Fan_nr_po       [#] Number of switched on Fans in the potato
storage
% fr_cooling_cc   [0/1] Carrot and celeriac cooling on/off
% num_eva_cc      [#] Number of switched on evaporators cc storage
% num_eva_un      [#] Number of switched on evaporators union storage

% Outputs:
% Fan_nr_un       [#] Number of switched on Fans in the union storage
% Fan_nr_po       [#] Number of switched on Fans in the potato
storage
% fr_vent_out_un  [0-1] Fraction of outside air union ventilation
% fr_vent_out_po  [0-1] Fraction of outside air potato ventilation
% fr_cooling_un   [0/1] Union cooling on/off
% fr_cooling_po   [0/1] Potato cooling on/off
% fr_cooling_cc   [0/1] Carrot and celeriac cooling on/off
% num_eva_cc      [#] Number of switched on evaporators cc storage
% num_eva_un      [#] Number of switched on evaporators union storage
% Energy_result   [J/h] Energy netto flow at the end

%% Setpoints Settings

%Unions
T_un_set = 4.5;           % [C] Setpoint temperature of unions
T_un_dev = 0.3;          % [C] Maximum deviation from setpoint

T_un_lb = T_un_set - T_un_dev; % [C] Union temperature under bound
T_un_ub = T_un_set + T_un_dev; % [C] Union temperature upper bound

% Seed potatoes
T_po_set = 4.0;          % [C] Setpoint temperature of the seed
potatoes
T_po_dev = 0.3;          % [C] Maximum deviation from setpoint
```

```

T_po_lb = T_po_set - T_po_dev;           % [C] Seed potato temperature under
bound
T_po_ub = T_po_set + T_po_dev;           % [C] Seed Potato temperature upper
bound

% Carrots and Celeriac
T_cc_set = 1.0;                           % [C] Setpoint temperature of carrots
and celeriac
T_cc_dev = 0.1;                           % [C] Maximum deviation from setpoint

T_cc_lb = T_cc_set - T_cc_dev;           % [C] C&C temperature under bound
T_cc_ub = T_cc_set + T_cc_dev;           % [C] C&C temperature upper bound

%% Temperature vector
Temp_space_un = T_un_ub - T_un;           % [C]
Temperature space left unions
Temp_space_po = T_po_ub - T_po;           % [C]
Temperature space left seed potatoes
Temp_space_cc = T_cc_ub - T_cc;           % [C]
Temperature space left carrots and celeriac

Temp_space_vector = [Temp_space_un Temp_space_po Temp_space_cc]; % [C]
Vector with the temperature spaces of all the storage facilities

[ord_temp_space] = sort(Temp_space_vector); % [C]
Order the temperature space vector from the smallest value to the highest

%% Conversion
Energy_prod_watts_start = Energy_prod / 3600; % [W]
Transform the energy production of the hour towards Watts

%% Reset
% Switch all the cooling and ventilation equipment off

fr_cooling_un = 0;
fr_vent_out_un = 0;
Fan_nr_un=0;
num_eva_un=0;

fr_vent_out_po = 0;
fr_cooling_po = 0;
Fan_nr_po=0;

fr_cooling_cc=0;
num_eva_cc = 0;

%% Necessary cooling

% Unions
if T_un >= T_un_ub ;                       % In case the union
temperature is higher than the maximum allowed temperature, necessary
action is needed
    Fan_nr_un=8;                             % When necessary
action is needed, all the fans will be switched on.

```

```

    if T_un >= Tout % When the union
temperature is higher than the outside temperature, it is possible to cool
with outside air
        fr_vent_out_un = (T_un_lb-T_un)/(Tout-T_un); % [0-1] fraction
outside air for ventilation to get the right ventilation temperature
        if fr_vent_out_un >=1; % Cannot be more
than 1 or 100% outside air
            fr_vent_out_un = 1;
        else
        end
        fr_cooling_un = 0; % Artificial cooling is off when cooled
with outside air
        num_eva_un =0; % Evaporators are off when cooled with
outside air
    else
        fr_vent_out_un = 0; % if outside air is higher than inside
air, don't ventilate with outside air
        fr_cooling_un =1; % Artificial cooling is switched on
        num_eva_un=2; % Both 2 evaporators are switched on
    end
elseif T_un<=T_un_lb; % If the union temperature is lower
than the lower bound temperature, switch off all
    fr_cooling_un = 0;
    fr_vent_out_un = 0;
    Fan_nr_un=0;
    num_eva_un=0;

end

% Seed potatoes
if T_po >= T_po_ub % In case the
potato temperature is higher than the maximum allowed temperature,
necessary action is needed
    Fan_nr_po=2; % When necessary
action is needed, all the fans will be switched on.
    if T_po >= Tout % When the potato
temperature is higher than the outside temperature, it is possible to cool
with outside air
        fr_vent_out_po = (T_po_lb-T_po)/(Tout-T_po); % [0-1] fraction
outside air for ventilation to get the right ventilation temperature
        if fr_vent_out_po >=1; % Cannot be more
than 1 or 100% outside air
            fr_vent_out_po = 1;
        else
        end
        fr_cooling_po = 0; % Artificial cooling is off
    else
        fr_vent_out_po = 0; % if outside air is higher than inside
air, don't ventilate with outside air
        fr_cooling_po =1; % Artificial cooling is switched on
    end
elseif T_po<=T_po_lb; % If the potato temperature is lower
than the lower bound temperature, switch off all
    fr_vent_out_po = 0;
    fr_cooling_po = 0;
    Fan_nr_po=0;
end

```

```

% Carrots and Celeriac
if T_cc >= T_cc_ub % If T_cc exceeds the maximum
temperature, necessary cooling action is needed
    fr_cooling_cc = 1; % [0-1] 0 = off, 1 = on.
    num_eva_cc = 3; % number of switched on evaporators

elseif T_cc<=T_cc_lb; % If T_cc goes below the minimum
temperature, switch off all the cooling.
    fr_cooling_cc=0;
    num_eva_cc = 0;
end

%% extra additions
Energy_prod_watts = Energy_prod_watts_start - (Fan_nr_un * 2957 +
fr_cooling_un * ((34600*num_eva_un)/4))- (num_eva_cc * 51300/4)- (Fan_nr_po
* 1651 + fr_cooling_po * (40000/4)); % Energy left after the necessary
cooling

if Energy_prod_watts>=1 % If there is energy left, start searching
for extra cooling possibilities
    loop_nr=1;
else
    loop_nr=4; % If there is no energy left, the system
will not seek for further cooling possibilities
end

while loop_nr <=3 % 3 storage facilities, so 3 loops to see
for every storage if cooling actions are possible
    if Energy_prod_watts >=0 % If there is still energy left, search for
possibilities
        % Extra union addition
        if Temp_space_un == ord_temp_space(loop_nr) % If the loop
number corresponds with the order of temperature space within the
boundaries.
            if Fan_nr_un == 0; % If the cooling is
off (so not switched on in the necessary part)
                % next part is like the necessary part, differences
                % will be added.
                if T_un >= T_un_lb;
                    if T_un >= Tout
                        fr_vent_out_un = (T_un_lb-T_un)/(Tout-T_un);
                    % [0-1] fraction outside air for ventilation
                    if fr_vent_out_un >=1;
                        fr_vent_out_un = 1;
                    else
                        end

                    Fan_nr_un = floor(Energy_prod_watts/2957);
                    % How many fans are possible to use for outside ventilation
                    if Fan_nr_un >=8
                    % A maximum of 8 fans can be used because there are not more installed
                    inside the storage
                        Fan_nr_un = 8;
                    elseif Fan_nr_un ==0
                    % If no fan can be switched on, than the no fraction for outside
                    ventilation is needed

```



```

    Energy_prod_watts = Energy_prod_watts_start - (Fan_nr_un * 2957 +
fr_cooling_un * ((34600*num_eva_un)/4))- (num_eva_cc * 51300/4)- (Fan_nr_po
* 1651 + fr_cooling_po * (40000/4)); % Calculate the energy left after
possible new switched on equipment

```

```

    % Extra seed potato addition
    if Temp_space_po == ord_temp_space(loop_nr)
        if Fan_nr_po == 0;
            if T_po >= T_po_lb;
                if T_po >= Tout
                    fr_vent_out_po = (T_po_lb-T_po)/(Tout-T_po);
% [0-1] fraction outside air for ventilation
                    if fr_vent_out_po >=1;
                        fr_vent_out_po = 1;
                    else
                        end
                    Fan_nr_po = floor(Energy_prod_watts/1651);
                    if Fan_nr_po >=2
                        Fan_nr_po = 2;
                    elseif Fan_nr_po ==0
                        fr_vent_out_po = 0;
                    end
                else
                    fr_vent_out_po = 0;
                    if Energy_prod_watts>= ((40000/4)+1651);
                        fr_cooling_po=1;
                        Fan_nr_po = floor((Energy_prod_watts-
(40000/4))/1651);
                        if Fan_nr_po >=2
                            Fan_nr_po = 2;
                        else
                            end
                        else
                            fr_cooling_po=0;
                            Fan_nr_po = 0;
                        end
                    end
                end
            end
        end
    end
end

```

```

    Energy_prod_watts = Energy_prod_watts_start - (Fan_nr_un * 2957 +
fr_cooling_un * ((34600*num_eva_un)/4))- (num_eva_cc * 51300/4)- (Fan_nr_po
* 1651 + fr_cooling_po * (40000/4));

```

```

    % Extra carrot and celeriac addition
    if Temp_space_cc == ord_temp_space(loop_nr)
        if fr_cooling_cc == 0;
            if T_cc >= T_cc_lb;
                if Energy_prod_watts >= (51300/4);
                    fr_cooling_cc=1;
                    num_eva_cc =
floor(Energy_prod_watts/(51300/4));
                    if num_eva_cc >=3

```

```

                                num_eva_cc =3;
                                else
                                end
                                else
                                fr_cooling_cc=0;
                                num_eva_cc = 0;
                                end
                                end
                                end
                                end
                                end
                                else
                                end
                                Energy_prod_watts = Energy_prod_watts_start - (Fan_nr_un * 2957 +
                                fr_cooling_un * ((34600*num_eva_un)/4))- (num_eva_cc * 51300/4)- (Fan_nr_po
                                * 1651 + fr_cooling_po * (40000/4));

                                loop_nr = loop_nr +1;
                                end
                                Energy_result = (Energy_prod_watts_start - (Fan_nr_un * 2957 +
                                fr_cooling_un * ((34600*num_eva_un)/4))- (num_eva_cc * 51300/4)- (Fan_nr_po
                                * 1651 + fr_cooling_po * (40000/4)))*3600; %[J/h]
```

