Design of an intelligent controller for a renewable energy efficient bulk storage tank

Conference Paper · January 2015

Rupert Gouws
North West University South Africa

DESIGN OF AN INTELLIGENT CONTROLLER FOR A RENEWABLE ENERGY EFFICIENT BULK STORAGE TANK

W.A. Pelser* and R. Gouws*

** North-West University, School of Electrical, Electronic and Computer Engineering, Potchefstroom, Email: 22704515@nwu.ac.za*

Abstract: The national electricity supplier in South Africa is experiencing difficulty in providing the required electricity, due to compliance with environmental regulations and the continuous price increase of commercial fuels. Making use of renewable energy solutions and energy efficient systems in everyday applications would address this problem. This project focusses on cooling systems, and illustrates an energy efficient cooling system by making use of a pre-cooler for a bulk storage tank. The cooling tank uses thermoelectric cooling modules (TECMs) to cool the milk before it is added to the actual bulk tank, and is controlled by a programmable logic controller (PLC). A small scale model of an actual tank was used to perform tests, which indicated the abilities of the cooling system. Further Solidworks® simulations were done by implementing the measured results, where after it was decided to make use of a pre-cooler, instead of adding the system to a traditional cooling system. A solar power system to power the TECMs was also designed by making use of PVSyst® simulations.

Keywords: renewable energy; energy efficiency; PLC; TECM; bulk storage tank; cooling system; solar power design.

1. INTRODUCTION

South Africa has been reported to be entering a dark age in terms of the availability of electrical energy, resulting in regular and unexpected power outages [1, 2]. By implementing more energy efficient systems in everyday life, and additionally making use of renewable energy sources, a great deal of the strain to provide electricity can be relieved from Eskom.

This study focuses on making cooling systems more energy effective, and it was decided to demonstrate such a system by making use of a bulk tank's cooling system, used on dairy farms. The lifetime of the milk that is stored in the tanks is shortened by power outages, causing losses for the farmer. The cost of electricity for cooling the milk and keeping the temperature constant is another problem for the farmers. These increased costs are a great threat to the agricultural sector, as the number of dairy farmers in South Africa has decreased by about 5 000 in the past 10 years [3, 4]. A solution which reduces the cost of providing milk, and simultaneously reduces the strain on the national electricity supplier to provide electricity would be a promising development in the field.

There are already several cooling methods available for use in bulk tanks which works very sufficiently, but not necessarily energy efficiently. It was thus decided to make use of TECMs as the cooling mechanism and testing it as the sole cooling device in a small-scale model of an actual tank. TECMs have also been used as part of an air-conditioning system in a previous project in [5], and a TECM holder for vaccines in [6]. Further relevant research that has been done with regards to this project is all of the research on developments in the solar power industry. Results from such research are used to design the solar power system needed to operate the TECMs in the cooling system.

Past research has focused on the use of cooling units and making it more energy efficient, as well as on renewable energy sources. The research discussed in this article focuses on the combination of all of the different technologies, and makes use of practical tests on a small scale to validate simulation results before making final assumptions. The PLC is also used as a control device, which is not used in traditional milk cooling systems. The farmer will benefit by this, as it intelligently controls the energy sources for TECMs, as well as ensures that the TECM does not use unnecessary power. The PLC will further measure the capacity of the tank's content, ensuring accurate measurements.

Against this background, it is seen that the main problem to be addressed is the implementation of energy efficient products in everyday life, with support from renewable energy sources. This will be done by investigating generally used cooling systems, with specific focus on bulk tanks used in dairies. Research in this field would thus benefit the dairy farmer, as well as the agricultural sector of South Africa. The design of the intelligent, energy efficient bulk tank was done by first building a small-scale model of an actual tank, and performing various tests on it to verify the simulated results. These results were used in further simulations to design the actual tank, while a solar power system was also designed for this system. The modified system making use of the TECMs and solar power has to be compared to the traditional cooling system of a bulk tank, in order to observe its effect. It is important to find the balance between cost and effectiveness of the TECMs, and to determine up to which point its implementation would still be useful and economically feasible.

The remainder of this paper will discuss a literature review of some of the main components that were used in the system, as well as the methodology that was followed in the pursuit of finding a solution to the stated problems. The results obtained from testing the small scale model and the design decisions made from it will then be given, followed by a discussion summarising the findings of the study.

2. LITERATURE REVIEW

This literature review will only highlight the main critical components that were used in the design of the system. These components are the renewable energy source, controller, and cooling device. Other components that were also investigated in the original literature study for this project is the storage batteries, charge controller, additional energy source, holder, temperature sensors, and liquid level sensor. The literature study investigated a variety of different products that are available for use as a certain component in the system. This literature review will, however, focus only on the products that were chosen for each component, and will thus not discuss all of the alternative options.

2.1 Renewable energy source

South Africa as a whole has been reported to be responsible for approximately 2% of the greenhouse gas emissions in the world, even though it only has about 1% of the population [7]. This emphasises the need for the implementation of more renewable energy sources in the country. The intended operating environment and implementation of the energy source also has to be considered, implying that the choice is not only made by choosing the most cost-effective and environmentally-friendly solution. For the environment of a dairy farm, and the relevant size of the system, it was decided that a solar power solution would be the most effective choice.

Figure 1 shows the global horizontal irradiation map for South Africa [8]. This is reported to be the most important parameter to be used for the evaluation of solar energy use in a specific region, and is also the most basic value used when doing photovoltaic (PV) simulations [8]. As can be seen in Figure 1, most parts of South Africa have a very high average irradiation, as the standard measurement is expected to be about 1000 W/m^2. The average daily irradiation of the Earth is approximately 250 W/m^2 for an entire year [9]. This is due to the fact that irradiation is lower in winter months, causing a decrease in the yearly average. The map in Figure 1 shows the irradiation for South Africa in terms of the average annual sum over seven years. When converting the general average of 250 W/m^2 to an annual sum, by multiplying it with the number of hours in a year (8760 hours), it can be seen that the average annual sum is about 2190 kWh/m^2.

In Figure 1 all of the regions that is an orange colour is above the average of 2190 kWh/m^2. When viewing the map, it can be seen that more than half of the country has an above average annual irradiation, making it a potential area for the implementation of solar power. The Potchefstroom area, where the project was completed, falls inside an orange area, implying that solar power is a viable choice for use as a renewable energy source. Additional to the irradiation, the air mass (thickness and clarity of the air) and the temperature of the module is also taken into account when deciding whether or not solar power is an appropriate solution [9]. Different manners for generating electricity by means of solar power are with single-crystalline PV panels, poly-crystalline PV panels, and amorphous silicon panels.

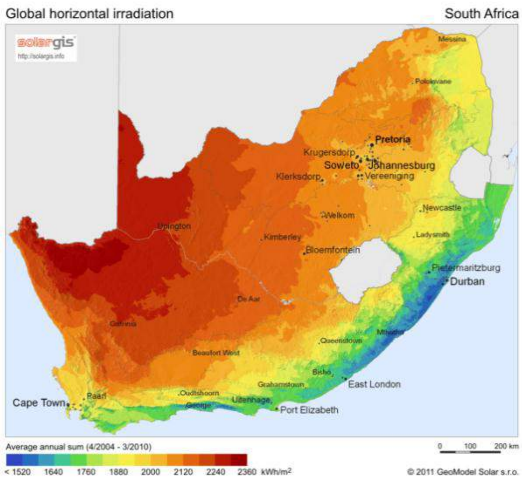

Figure 1: Global horizontal irradiation in South Africa [9]

The final decision was to make use of poly-crystalline PV panels, based on criteria that includes, but are not limited to, the initial cost, and small-scale efficiency. The poly-crystalline cells that are used to construct these panels are made from numerous silicon crystals of varying size (as shown in Figure 2), that is melted, poured into a mould, and crystallised in an imperfect manner. This process of construction makes the manufacturing of the polo-crystalline PV panels less expensive than the single-crystalline PV panels. These panels are, however, only about 12% effective in converting solar power to electricity, making it less efficient than the previously mentioned panels [10, 11].

Figure 2: Silicon crystals to be melted [12]

2.2 Controller

In this specific system, the controller receives inputs such as the level of the milk inside the tank, and the temperatures of several thermometers. Depending on the level of the milk inside the tank, the controller will determine which sensor should be used as the critical sensor to indicate the temperature of the milk. The level of the milk will also activate and deactivate certain aspects of the system, for example when the level of the milk is very low, the milk mixer would not be effective and is deactivated. The volume of the contents of the tank is also determined in litres from the level of the milk, and it is displayed to the operator.

The controller further has to be able to switch intelligently between the renewable energy source and the solar power, and be able to switch the cooling system on and off, depending on the temperature measured by the critical sensor. A dairy is typically situated and operated in quite harsh conditions, implying that the controller should be able to handle such conditions. Among the controllers that were considered for use were a PLC, Arduino, Raspberry PI, Panda board, and Beagle board. It was decided to use the PLC as the control unit, as it is easy to use and implement, and it would be sufficient for the system and applicable to the conditions.

A PLC is reported to be a compact, universally applicable, easy to operate control device that is easy-to-use and can control any simple control task without any effort. The “Siemens LOGO!” module that was used is convenient and user-friendly for simple open- and closed-loop control tasks, but can be implemented universally. This module has a number of built in basic functions that can be easily accessed, with new functions and programs that can be generated with the use of PC software. The module can also be connected to a PC to demonstrate the working of the control unit, and even to obtain required measurements [13].

2.3 Cooling device

TECMs were suggested by the client as cooling devices and have been used in previous final year projects [5] and [6] - in 2012 as part of a “TECM holder” for vaccines, and in 2013 as part of a “Mini TECM Solar Air Conditioning System”. The devices will thus not be investigated in full again, as the same TECM devices are to be used for this project, and has already been purchased. The TECM to be used is a modified version for liquid cooling and will also be customized for simulation purposes.

TECMs are small devices based on the “Peltier effect”. Peltier, a scientist, found that if a voltage is applied to a thermocouple, a temperature difference can be found between the junctions. The working of a TECM is shown in Figure 3 in a very simplified form. This image shows that when DC power is applied to the device, the one side of the device will become warmer, and the other side will cool down. This results in a specific temperature difference, depending on the module chosen from the available variety [14].

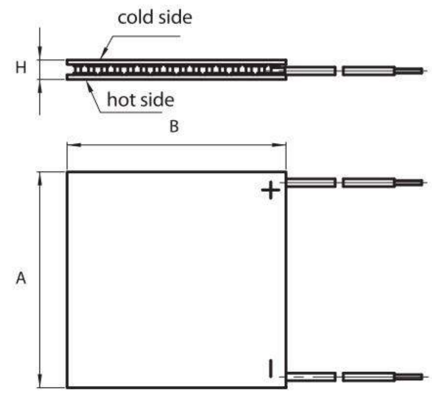

Figure 3: Working of a TECM [14]

2.4 Remaining components

The remainder of the components that were used in the project were also discussed in the literature study, and the desired products were chosen based on specified criteria for each component. The component choices are listed in Table 1.

Table 1: Component Choices

Component	Chosen product
Renewable energy source	Poly-crystalline solar panels
Alternative energy source	Eskom power grid
Controller	PLC
Cooling device	TECM
Holder	Bulk storage tank
Temperature sensor	Thermistor
Liquid level sensor	eTape
Storage battery	Lead-acid battery
Charge controller	PWM charge controller

3. METHODOLOGY

The method that was used to achieve the completion of this project and to be able to obtain the required results is the typical engineering design process. This included identifying the problem; deciding on- and confirming the specifications with the client; doing research to decide upon the best choice of components for each element of the system; designing and simulating the end product; testing the system; and processing the obtained results. This section of the paper will, however, focus on the designing, building, and testing methods that were used to obtain the results that will be discussed in the following section.

After conducting the literature study and deciding upon the components in Table 1 to be used in the system, the detail design of the end product had to be initiated. This required choosing the exact components to be used in the tank, and how it would be implemented. The tank that was used is a 25:1 scaled model of an actual 1500 l bulk storage tank. The Laird Technologies LA-115-24-02-0710 liquid cooled TECM assembly [15] was used as the cooling device, with pipes being placed in direct contact with the milk inside the tank for better efficiency. 99.7% pure ethanol was circulated through the pipes and cooled by the TECM. LM35 temperature sensors were modified to be waterproof by making use of the method described in [16], as well as a PT100 sensor which was already available and is much more accurate. The eTape was applied to the side of the tank as a liquid level sensor as instructed in [17], and connected by making use of a voltage divider circuit.

The basic setup of the inside of the tank, including the pipes for circulation, is shown in the simulated representation of Figure 4. The lines in the cross-section of the tank indicate four different levels at which the tank was simulated, and where the critical sensors were placed. During the initial simulations, assumptions about the operation of the TECM setup was made, and simulations were done at different levels, for different numbers of TECMs in the system. These simulations are, however, emitted from this paper, as it was redone later in the redesign with more accurate losses included from the test results, as in Figure 10.

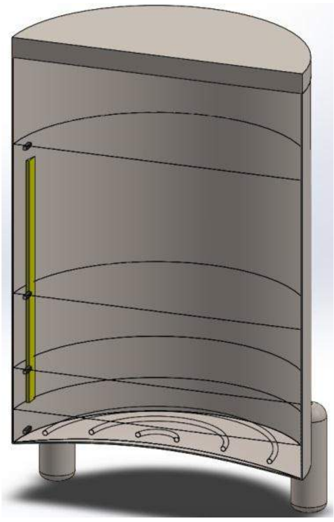

Figure 4: Inside of tank with relevant components

The Siemens LOGO! 0BA6 PLC was used as the controller, and the flow diagram for the control of the level- and temperature sensors is shown in Figure 5. A flow diagram for the switching between the two energy sources was also drafted, but is not presented in this paper, as the solar panels were merely simulated, and not implemented in the actual system. After all of the subsystems were in separate working conditions, they were added together to represent the small-scale prototype for testing.

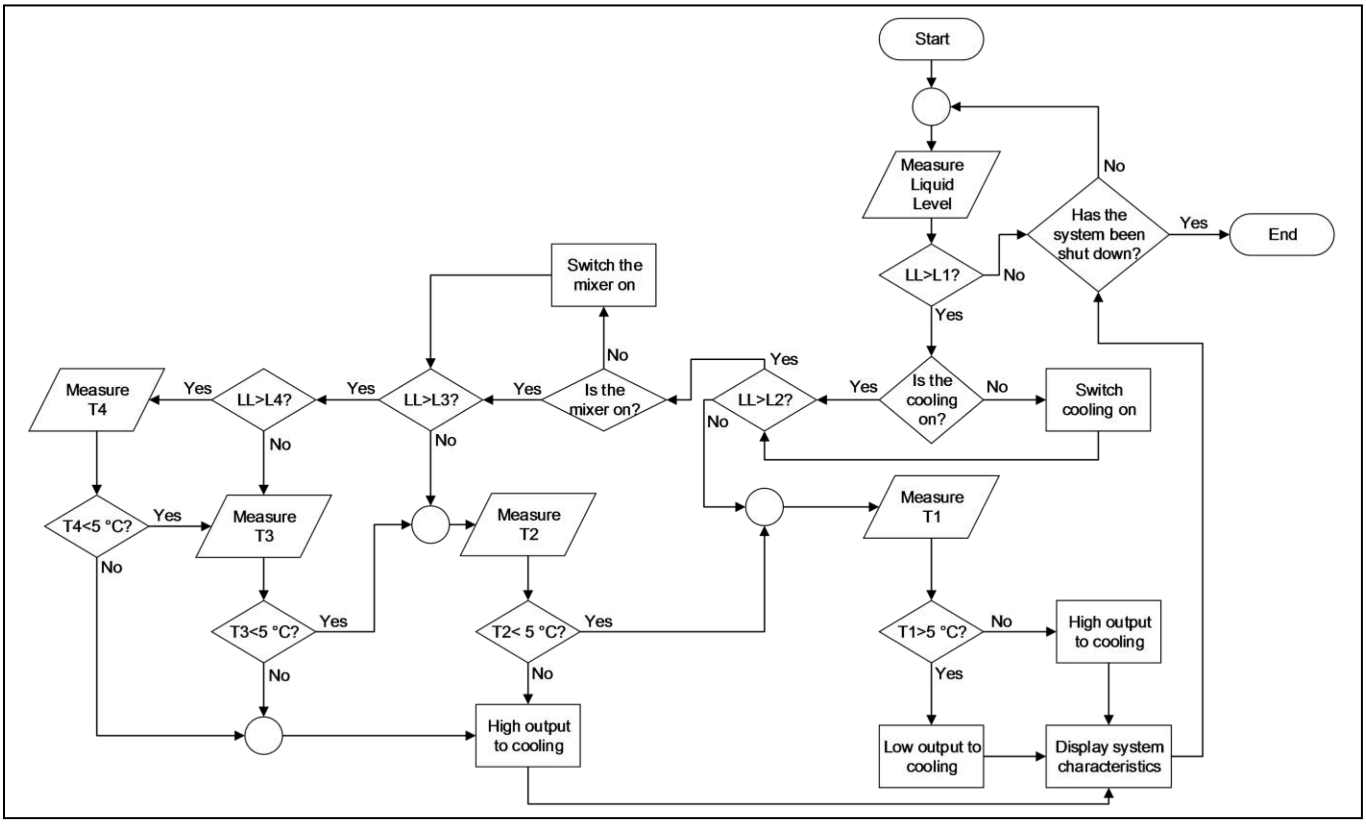

Figure 5: Sensors and outputs flow diagram

The circuitry included 5 V and 9 V voltage regulators, as the temperature sensors requires 5 V for operation and the milk mixer and eTape requires 9 V. The rest of the system was operated at 24 VDC.

After all of the components were added together, the testing of the tank could begin. Two main tests were performed to determine the effectiveness of the cooling system in the tank, in order to simulate the tank correctly. According to the "Agricultural Products Standard Act of 1990" [18], the milk has to be cooled to a temperature of below 5 °C within a period of 3 hours. The milk is expected to enter the tank at a temperature of about 38 °C, which is the body temperature of the cow [19]. During the performing of the tests, the current was measured in order to generate graphs of the energy used by the system. This made it possible to determine the required characteristics of the solar power system. The two tests that were performed are listed below.

- Test 1: The first test was to determine within which period of time, and to what temperature the system is able to cool the milk from a starting temperature of 38 °C. While performing this test, two different methods of operating the system were also tested, in order to determine which method is more effective in terms of cooling capabilities, and comparing it to the energy efficiency of one another. The first method was to keep all components of the system active during the entire process. The second method was to switch the circulation of the ethanol through the pipes on for 1.5 minutes, and then off for 3.5 minutes, while simultaneously switching the milk mixer on and off for 5 minutes at a time. These tests had to be performed for a minimum time duration of 3 hours.
- Test 2: The second test the was performed was to determine the ability of the system to keep the temperature below the required 5 °C, but still above -0.5 °C, which is the freezing point of milk [19]. This test was performed by adding milk to the tank at a temperature of below 5 °C, and observing the temperature change and power dissipation for a period of at least 2 hours.

4. RESULTS

This section discusses the results of the two tests that were performed, as described previously. The tests were performed on the small-scale prototype, as shown in Figure 6. This figure shows the inside of the tank, containing the coil through which ethanol was pumped for the liquid cooling, the eTape liquid level sensor, temperature sensors, and the mixer for the milk. The sensors are exported to the outside of the tank through a small hole, and connected to the relevant circuitry. The circuitry is again connected to the PLC, in order to provide all of the necessary inputs to the control system.

Figure 6: Inside of physical tank that was tested

The result of the first test is shown in Figure 7. As can be seen, the two methods give a very similar temperature drop from 38 °C, and both methods were only able to cool the temperature to about 15 °C after 4 hours. This indicates that it does not matter which method is used in terms of the change in temperature. These results will also be implemented in the simulations. The one liquid cooled TECM setup that was used in the system was very effective in cooling the temperature from 38 °C to about 20 °C, where after the fall in the temperature became very slow. The tests were conducted at liquid level 1. The graph also shows a third order polynomial trendline for the results, accompanied by a representing equation. The R^2 value of the trendline is also given as 0.998, which indicates that the line is an appropriate representation of the date, as the value is close to 1.

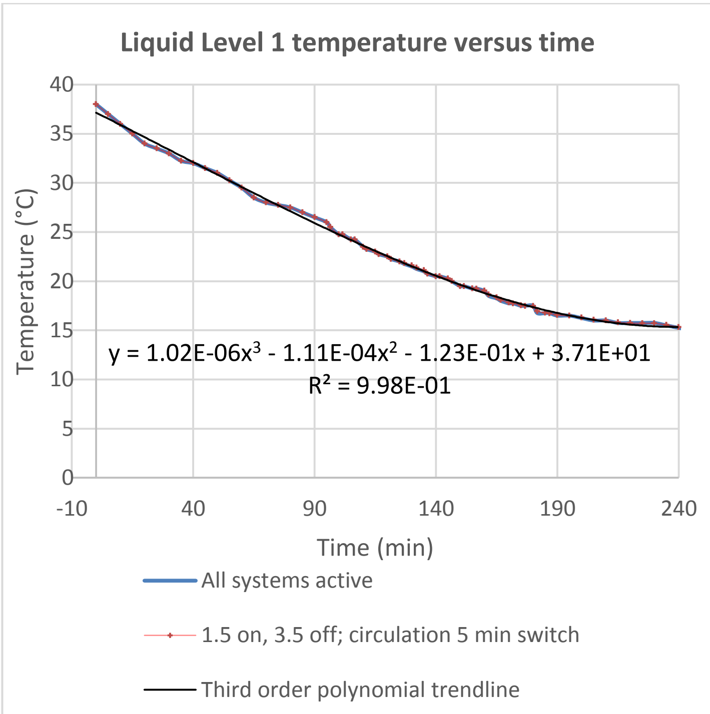

Figure 7: Test 1 temperature comparison

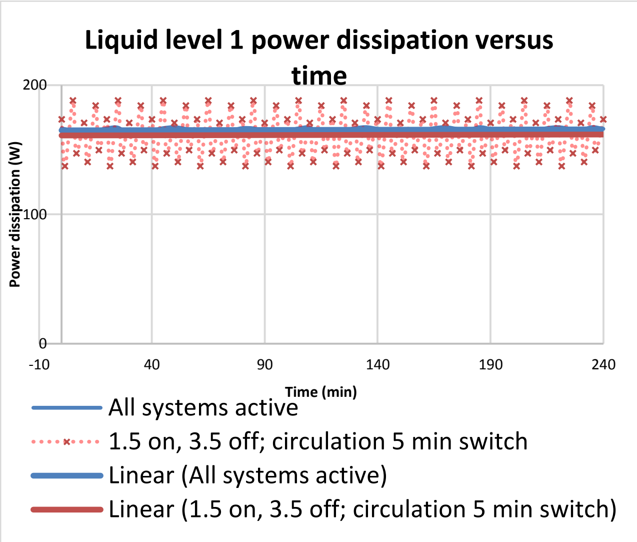

Figure 8: Test 1 power dissipation comparison

The comparison in the power dissipation of the two methods of test 1 is shown in Figure 8. As can be seen in this figure, the power dissipation of the second method changes periodically. A trend line representing the average power dissipation of this method has, however, also been drawn, indicating that the second method requires less power on average to operate than the first method. The power dissipation of the first method was determined as 165 W for the experiment, while the average power dissipation for the second method was determined to be 161 W during the test period. This indicates that the second method is more energy efficient, and is thus the method that will be implemented in the final design.

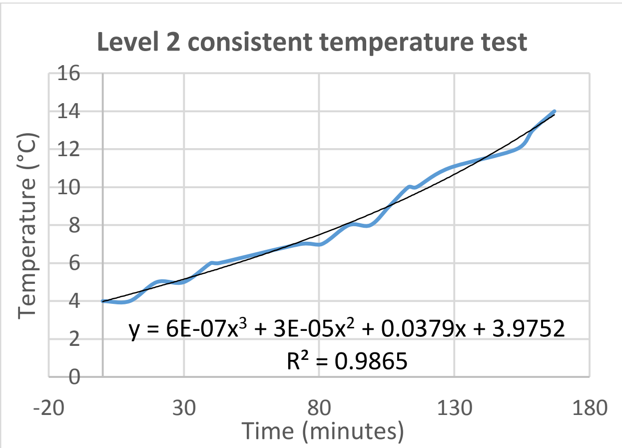

Figure 9: Test 2: Consistent temperature test

The second test that had to be done was the consistent temperature test. The test was conducted as described in the previous section, with an initial temperature of 4 °C, and the tests being conducted at liquid level 2. The resulting temperature of this test is shown in Figure 9. The test was conducted for a period slightly shorter than 3 hours, and indicated that one liquid cooled TECM setup will not be able to keep the temperature of the milk below 5 °C. The temperature rose above 5 °C after about 30 minutes, where after it continued to rise as shown in the graph. It was found that a third order polynomial equation fits the plot, and is added as a trendline in Figure 9, accompanied by the relevant equation. The R^2 value of 0.9865 proves that the equation is an acceptable representation of the data. The power dissipation for this test is about the same as that shown in Figure 8 for method 2, as the switching of the system components was done in the same manner.

5. DISCUSSION

The results can be interpreted to design a supporting cooling system for an actual tank by making use of simulations. The small-scale model was simulated for various numbers of TECM assemblies at different liquid levels, and it was decided that the most effective implementation would be to make use of the tank as a pre-cooler for an actual bulk tank, implementing six liquid cooled TECM assemblies. The pre-cooler would be able to reduce the temperature of the milk by 10 °C before it enters the bulk tank, with sufficient time left for the traditional cooling methods to further cool the milk to the required temperature. The resulting simulation with the six liquid cooled TECM setups is shown in Figure 10(a) and Figure 10(b).

The pre-cooling system in the design would only make use of solar power to operate, thus eliminating a great deal of strain from the electricity supplier. The results in Figure 9 proved that the system will not be able to keep the temperature below 5 °C. It is thus estimated that the system will only be active for about 6 hours per day: 3 hours per session with two sessions per day. The daily energy requirement of the tank is thus about 5.8 kWh for six TECM assemblies.

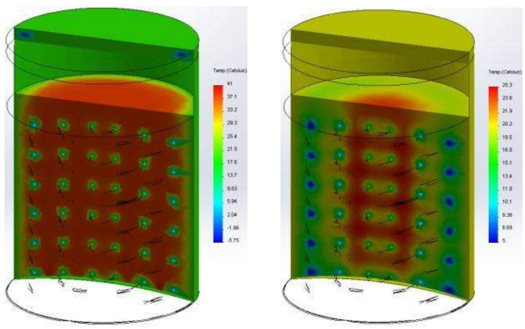

Figure 10: Simulation with six TECM setups: (a) after 5 minutes; (b) after 3 hours

The battery capacity was chosen to be for 12 hours in the simulations, in order to be able to operate the system for two days without charging the batteries from the solar panels. The minimum requirements for the solar panels and storage batteries were determined from the winter months (specifically June), when the solar irradiation is at its lowest. From the PVSyst® simulation results shown in

Figure 11, it is seen that the solar power needs to be able to provide 1271 W, and the 24 V batteries should have a capacity of 142 Ah.

The total estimated cost for the year 2014 for the solar panels is about R 16 253.22 [20], and about R 7 678.00 [20] for the lead-acid storage batteries. A liquid cooled TECM assembly would cost about R 4 000.00 [5], resulting in a cost of about R 24 000.00 for six assemblies. Other costs that also have to be taken into account is that of the temperature sensors, liquid level sensor, PLC, and mixer, which adds an amount of about R 4 550.00 to the total, as determined in the year 2014, and implemented in the test model of figure 6. The total cost to implement this system in the tank as shown in Figure 10 would thus be about R 52 481.22.

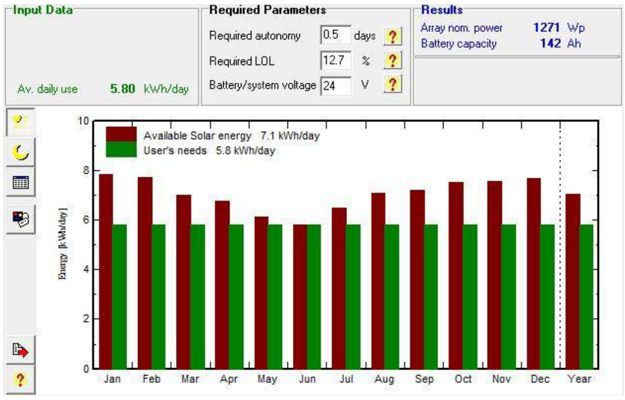

Figure 11: PVSyst® simulations for solar panel size and batteries

6. CONCLUSION

The main purpose of this project was to design an energy efficient cooling system, that would make use of a renewable energy source and thus relief strain from Eskom to supply electricity. The cooling system that was used as demonstration is a supporting cooling system for a bulk storage tank, which was tested practically in order to adapt the simulation to a more practical situation, and to take actual losses into account during the redesign process.

It was determined that by making use of six TECMs in a 60 litre tank as a pre-cooler for an actual bulk tank, the milk could be cooled by 10 °C from its initial temperature, and still leave sufficient time for a traditional bulk tank to cool the milk to the required temperature. This would however require an initial cost of about R 52 481.22 (estimated from prices received during the year 2014) to equip the pre-cooler and purchase solar panels and storage batteries. As each situation is unique in terms of how much milk is produced, etc. it has to be determined how many pre-cooling systems are required for each situation. The number of pre-coolers in the system can be adjusted by the dairy farmer, depending on the initial amount he is willing to pay.

7. REFERENCES

[1] L. Buthelezi and D. Pressly, "SA faces 'dark age' as Eskom struggles," *Business report,* 3 December 2013.

[2] H. Grover and M. Pretorius, "The technology assessment of demand side bidding within the South African context," in *AFRICON 2007*, Windhoek, 2007.

[3] A. Janeke, "Melkbedryf verloor 'n boer per dag," *Lanbou.com,* 16 July 2013.

[4] A. Stuijt, "Are S.A dairy farmers going extinct?," *Censorbugbear reports*, 17 July 2013.

[5] B. de Waal, "Mini TECM Solar Air Conditioning System," North-West - University Potchefstroom Campus, Potchefstroom, 2013.

[6] H. Eilers, "Thermoelectric (TECM) Cooling Holder," North-West - University Potchefstroom Campus, Potchefstroom, 2012.

[7] A. Meyer and D. Dintchev, "South Africa's electrical energy economy: environmental impacts, future developments and constraints," *Engineering Science and Education Journal*, vol. 7, no. 5, pp. 227 - 232, 2002.

[8] 2014 GeoModel Solar, "Solar radiation maps: Global Horizontal Irradiation (GHI)," Solar GIS, 2010-2014. [Online]. Available: http://solargis.info/doc/71. [Accessed 9 March 2014].

[9] R. F. Pantelimon, M. Adam, M. Andrusca and C. Pancu, "Aspects Regarding Solar Battery Charge Controllers," Faculty of Electrical Engineering, Department of Power Engineering "Gheorghe Asachi" Technical University of Iaşi , Iaşi, Romania , 2013.

[10] D. Chiras, The Homeowner's guide to renewable energy, Canada: New Society Publishers, 2006.

[11] Dako Power cc, "Three Photovoltaic Technologies: Monocrystalline, Polycrystalline and Thin Film," Dako Power, 2008. [Online]. Available: http://www.dako.co.za/photovoltaic_types.html. [Accessed 9 March 2014].

[12] Ridders-Solar BVBA, "Polycrystalline Silicon," Ridders-Solar, [Online]. Available: http://www.ridders-solar.com/poly.shtml. [Accessed 12 April 2014].

[13] Siemens AG Industry Sector, "LOGO! logic modules," Siemens, 2008. [Online]. Available: https://eb.automation.siemens.com/mall/catalog/products/5000562. [Accessed 17 March 2014].

[14] M. Deng, A. Inoue and S. Goto, "Operator based Thermal Control of an Aluminum Plate with a Peltier Device," in *Innovative Computing, Information and Control, 2007. ICICIC '07. Second International Conference*, Kumamoto, 2007.

[15] Laird Technologies, "LA PowerCool Series, LA-115-24-02 Thermoelectric Assembly," 2010. [Online]. Available: www.lairdtech.com/WorkArea/DownloadAsset.aspx?id=5308. [Accessed 11 May 2014].

[16] "Waterproof DS18B20 Digital temperature sensor + extras," Adafruit, 2014. [Online]. Available: http://www.adafruit.com/products/381. [Accessed 25 May 2014].

[17] Milone Technologies, Inc., "eTape Operating Instructions and Application Notes," New Jersey, 2009.

[18] Dairy Standard Agency, "Code of practice for milk producers," [Online]. Available: http://www.landbou.com/content/uploads/ArticleDocument/COP_for_Milk_Producers_Oct_2013_s.pdf. [Accessed 24 January 2014].

[19] S. Rath, About Cows, Minocqua: Heartland Press, 1987.

[20] Imperial Crown Trading, "Solar Panel prices," Sustainable.co.za (Pty) LTD - Online Eco Store, 20114. [Online]. Available: http://www.sustainable.co.za/catalogsearch/result/?q=poly. [Accessed 26 May 2014].