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A simulated energy monitoring system to enable undergraduate engineering students to grasp fundamental energy generation principles

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Abstract: Engineering students must be equipped with the right graduate attributes in order to contribute effectively to the socio-economic growth of their communities. These vital attributes may be demonstrated by students through the use of various educational technologies, including computer based simulations. The purpose of this paper is to describe the design of a simulated energy monitoring system that was developed at the Central University of Technology to enable freshmen engineering students to grasp fundamental energy generation principles relating to solar energy. This system enables students to grasp principles of energy flow in a typical PV system, as well as the importance that power efficiency exerts on the overall performance of the system. The majority of students exposed to this system have indicated that they enjoyed the simulations, having applied new knowledge in a practical environment.

Keywords: LabVIEW, PV, education, visual, kinaesthetic

1. INTRODUCTION

"During my travels in Iraq, Israel, Gaza, Brazil, Indonesia, Japan, Europe and all over the United States, I have seen and heard the voices of people who want change. They want the stabilization of the economy, education and healthcare for all, renewable energy and an environmental vision with an eye on generations to come" [1]. These words by the musician, Michael Franti, point to society's desire for a more sustainable future. This sustainable future requires energy monitoring, in order to ascertain the level and quality of sustainability. This monitoring leads to energy management which refers to an efficient and effective use of energy to minimize cost, improve energy efficiency, and reduce greenhouse gas [2]. This efficient and effective use of energy often requires some or other form of control.

Dynamic modelling and computer based simulations (CBS) are valuable tools for product and process understanding, design, optimisation and control [3]. This aspect of control is especially important in renewable energy systems in order to mitigate energy losses and improve system efficiency. Moreover, interactive CBS can provide an "interactive-learning environment" in which participants can apply what they have just learned in a dynamic scenario, receiving instant feedback and being able to reflect on what can be improved through trial and error [4]. This improvement of the system is once again achieved through some or other control mechanism, where students can almost instantaneously visually observe the effects of their decisions. This brings to mind the various learning styles of students.

CBS created in software packages, such as MATLAB or LabVIEW, appeals to a wide range of student learning styles, including inductive, sequential, active and visual learning styles. In fact, previous research has shown how an ARDUINO board can be integrated with MATLAB to achieve specific learning objectives and provide a successful engineering experience for freshman engineering students [5, 6]. Academics therefore need to adjust their preferred teaching styles to accommodate the diverse learning styles of students [7] and to understand the connection between particular forms of educational technology and their effects on learning and teaching styles [8]. CBS are therefore key educational technologies which may be used to achieve this goal.

CBS are used in the training of engineering students when it is difficult or impossible to expose them to real life contexts or equipment. Research has shown that CBS can provide opportunities for students to perform experimental manipulations that would be inaccessible in real-life [9]. However, simulations are not ideal and it is therefore important for the academic to understand the limitations of this educational technology. Only then can appropriate guidance be provided to students in order to help them bridge the gap between the theoretical and practical instruction. Some disadvantages of using CBS in engineering education are that they can be expensive, time consuming to develop and difficult to grade [10]. Advantages of CBS can include the fact that it allows the student to freely vary specific parameters and observe the related effects, explore theoretical principles or systems under extreme conditions, allow for a detailed analysis of systems and are easily reproducible [11].

The purpose of this paper is to describe the design of a simulated energy monitoring system (SEMS) that was developed at the Central University of Technology (CUT) to help train freshmen engineering students in a renewable energy course. This SEMS is designed to help engineering students grasp fundamental principles of energy generation, which include energy efficiency, electrical energy flow, energy storage in a battery, energy usage and energy optimisation. The paper firstly explains the main energy generation principles, followed by the context of this study. Thereafter, the SEMS is introduced and explained followed by succinct conclusions.

2. ENERGY GENERATION PRINCIPLES

To enable students to grasp the operation of an energy generation system, with specific reference to a standalone PV system, requires understanding of energy flow, efficiency and storage. A simple analysis of the energy flow in a system is important in order to gain insights into the conversion process [12]. Maintaining a good energy efficiency is furthermore important for battery longevity [13],which is where the generated energy is stored.

The flow of electrical energy refers to the movement of electrons from the generating source to the storage device and associated loads. Students must be able to observe the input and output powers associated with each section of the energy system, thereby keeping track of the electrical energy flow. The main input power from the sun to the generating source (being the PV module in this case) is indicated in Watts/square meter (W/m^2) while the energy that is stored in the batteries (storage device) is indicated in Ampere hours (Ah). During direct sunlight hours, electrical energy will flow from the source to the storage device and then to the loads. During non-direct sunlight hours, students must be able to observe how the storage device is depleted, as it alone supplies energy to the load. The efficiency of the various components in the system plays a major role in the overall performance of the system, and is calculated using Equation 1.

$$\boldsymbol{\eta} = \frac{\boldsymbol{Pout}}{\boldsymbol{Pin}} \qquad (1)$$

Where

$\eta =$ Efficiency of component
$Pout =$ Output power
$Pin =$ Input power

However, students tend to better understand complex processes, like the flow of energy in energy generation systems when they actively participate in the simulation of these systems [14, 15]. This helps them to visualize the operation of the different sections within the system, thereby moving away from purely abstract thinking. Abstract thinking is difficult, as it takes a great deal of time to become familiar with theory at any level of depth [16]. However, the use of active experimentation in CBS (part of Kolb's Learning Cycle [17]) enables students to engage with the theory, eventually resulting in abstract conceptualization. The importance of helping students grasp these different energy generation principles is mandated by the logarithmic growth in renewable energy, including the construction of many solar farms.

3. CONTEXT OF THIS STUDY

In November 2013, the first solar farm of 75 MW (near Kalkbult) was connected to the South African National Grid [18]. Kalkbult was the first of many to follow. The Renewable Energy Independent Producers Procurement Programme, directed by the Department of Energy, has approved many projects for the Northern Cape, which is one of the provinces from where many CUT students emanate. This provides CUT with a unique opportunity to provide effective training to freshman engineering students regarding the operation, installation and maintenance of these renewable energy systems. This opportunity aligns itself with Vision 2020 of CUT which aims to be a centre of knowledge, innovation and excellence producing a critical mass of innovators that directly contributes to prosperity-creation [19]. One way of achieving this vision is by graduating an industry-ready workforce that possesses the right graduate attributes. These include problem solving, engineering design, communication, teamwork and technical competence.

Freshman engineering students at CUT may choose to enrol for a number of different National Diplomas or Certificates where these graduate attributes may be demonstrated. The National Diplomas usually requires a minimum of three years to complete, while the certificate requires one year of full time study. The certificate is designed to empower engineering students with the right graduate attributes to contribute to the socio-economic development of communities, societies and industry. The Higher Certificate in Renewable Energy Technologies (HCRET) has been offered at CUT since January 2014 and was specifically developed to supply technical competent people to the renewable industry in the Northern Cape and Free State. The HCRET is the first pre-graduate course in renewable energy that was approved by the South African Qualification Authority (SAQA) [20]. Successful completion of the HCRET indicates that students have been able to demonstrate the acquisition of specific learning outcomes (and subsequent graduate attributes) relating to the operation, design and installation of PV and Small Wind energy systems [21]. Digital Literacy, Academic Literacy, Mathematics I A and Mathematics I B are compulsory modules in this certificate (see Table 1), offered by service departments at CUT. The module entitled "Health and Safety: Principles and Practice" is offered by a professional service provider from within this field.

Table 1: Modules for HCRET [7]

Semester 1	Semester 2
Digital Literacy	Health and Safety: Principles and Practice
Academic Literacy and Communication Studies	Electrical Installation Practice
Mathematics I A	Power Generation and Storage
Electrical Engineering I	Solar Energy Systems II
Applied Physics of Energy Conversion	Small Wind Generation
Solar Energy Systems I	Mathematics I B

The SEMS was developed for the Solar Energy Systems II module which features 5 main sections. The introduction to solar energy covers basic concepts, principles, and definitions of energy generation. The next section introduces students to the different solar system configurations, including grid-tied and stand-alone systems. The third section covers aspects relating to PV system design, where the student must be able to design a complete PV system. Finally, AC and DC electrical measurements are discussed; students must be competent in their ability to safely do AC and DC measurements on a PV system. Many parts in the syllabus of Solar Energy Systems II can be addressed by the use of simulation.

4. LABVIEW SIMULATION INTERFACE

Figure 4 shows the LabVIEW user interface of a stand-alone PV system that was designed to be the control panel of the SEMS. The first section represents the energy source, namely the sun. The simulation illustrates a 24-hour cycle and can be used in two modes. In the first mode, the sun follows its daily orbit and the energy output follows the form of a bell-shaped curve reaching its peak at around 12H00. In this mode, the student has no control over the energy from the sun and the simulation reflects the normal daily radiation available from the sun, peaking at 1000 W/m^2. In the next mode, the student may manipulate the energy source to visually observe its effect on the subsequent sections.

The second section represents the PV array. This is where the student can change the output of the array from 0 to 1000 W. If, for example, a 100 W module is selected and the input from the sun is set at the Standard Test Condition (STC) of 1000 W/m^2, then the output of the module will be 100 W. The output of each section is shown in Watts to enable students to grasp energy efficiency principles. The dust and mismatch factor of the PV array is another setting in the PV array section. The typical value for dust and mismatch on a PV array is 15% [22], with students being able to control it in the SEMS with values between 8 and 15%.

The third section illustrates the charge controller that will charge the batteries as well as protect them from discharging beyond a recommended limit. Modern charge controllers have typical efficiencies of 97% [23]. Students may control the efficiency of the charger by varying it between 50 and 100%, again being able to visually observe its effect on subsequent sections.

The fourth section is the battery bank (storage device). The efficiency of the battery may also be altered between 80 and 100%, which is in line with current technology providing battery efficiencies of around 85%. It must be noted, though, that battery efficiencies are highly dependent on charging and discharging regimes as well as one the depth of discharge [24]. The battery's voltage, charge and state of charge are also indicated in this section.

The fifth section is the inverter where the student may once again set its efficiency between 80% and 100%. Current technology allow for inverter efficiency's in the order of 97% [25]. However, it must be noted that inverter efficiency is dependent on the AC load and may vary greatly over the operating range of the inverter [26].

The sixth section shows the losses in the wiring which can be controlled between 0% and 20%. Wiring losses include losses in electrical connections in the system as well as resistive losses that are affected by the length and diameter of the wires that are used [27].

Students may control the size of the load in the seventh section (0 to 200 W), visually observing the flow of energy from the storage section. The control panel of the SEMS is directly linked to the block diagram window available in LabVIEW, and is discussed in the next section.

5. LABVIEW SIMULATION CIRCUIT

The SEMS displays data for a one day period of 24 hour. If the simulation runs too quickly, then the student will not have time to interpret what is visually shown nor have time to control the various sections in order to optimize energy efficiency. This is set using the main loop time which is shown in Figure 1 to be 200 ms. It can also be seen that the main loop will repeat a total of 144 times at 200 ms each, resulting in a total simulation time of 28.8 s. This provides sufficient time for students to interact with the simulation, visually observing the effects of their decisions implement by the various controls. The simulation is set so that each sample represents 10 minutes of the 24 hour day. Three important parameters of the system is logged in the time domain over a 24 hour period and displayed on the control panel. These include the power from the PV array, the charge in the battery and the power to the load.

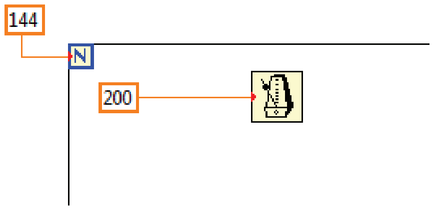


Figure 1: Loop timing in milliseconds

Figure 2 presents the components which are required for section 1 of the SEMS shown in Figure 1. A small part of the matrix that represents the values of the output of the sun is visible. The matrix consists of a set of 144 values that represents the bell-shaped curve of the sun's normal daily output.

Figure 3 illustrates the components of the second section shown in Figure 4. Here, the value of incoming solar radiation is divided by 1000, which equates to the STC of 1000 W/m^2. This implies that if the incoming solar radiation is 1000 W/m^2, then the sizing factor will be 1. This sizing factor is multiplied by the power rating of the

PV module to calculate the arrays output. Dust and mismatches in the array are expressed as a percentage in this section, which may also be controlled by the student. To calculate the correct multiplication factor, the control value is deducted from 100 and then divided by 100. This factor is then multiplied by the calculated PV output. As an example a dust and mismatch factor of 10% will result a multiplication factor of 0.9.

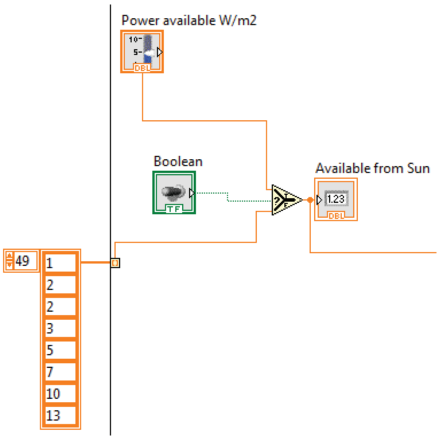


Figure 2: LabVIEW circuit of simulation mode selection

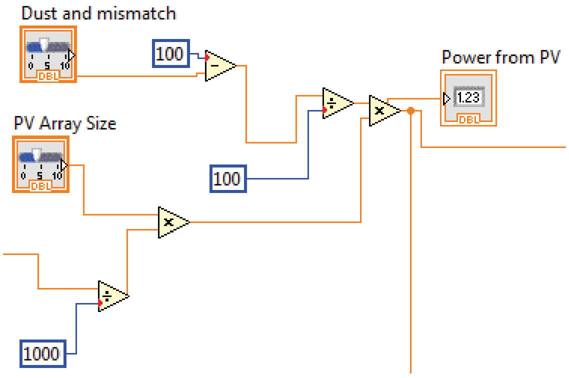
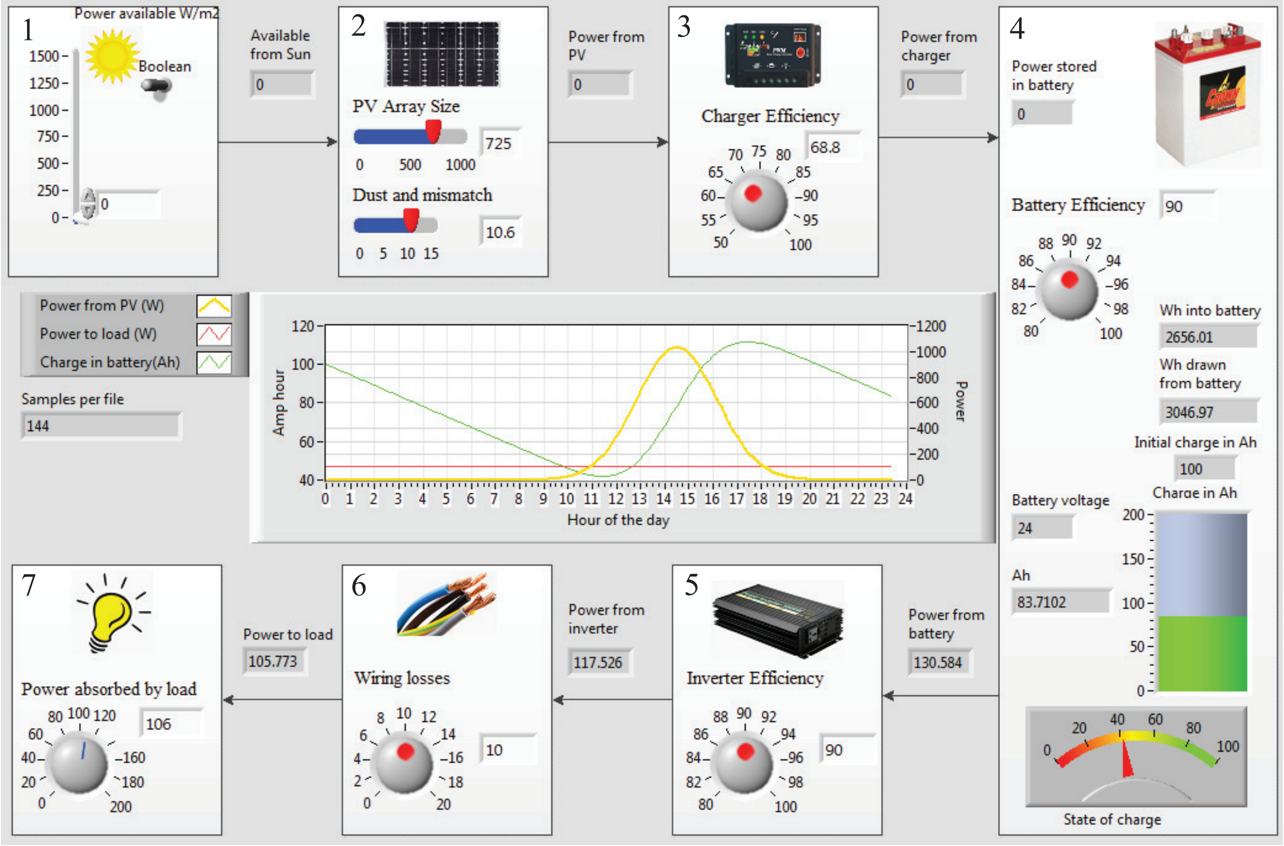


Figure 3: LabVIEW circuit of PV array

To calculate the output of the charge controller, the value of the PV array's output is multiplied with the efficiency of the charge controller (which may be controlled by the student) as shown in Figure 5. The same procedure is followed regarding the battery in order to obtain it efficiency factor as shown in Figure 6. This factor is multiplied with the output of the charge controller to determine how much of the input energy can be extracted from the battery after the losses have been accounted for.



Power available W/m2: 0

Boolean

Available from Sun: 0

PV Array Size: 725

Dust and mismatch: 10.6

Power from PV: 0

Charger Efficiency: 68.8

Power from charger: 0

Power stored in battery: 0

Battery Efficiency: 90

Wh into battery: 2656.01

Wh drawn from battery: 3046.97

Initial charge in Ah: 100

Battery voltage: 24

Ah: 83.7102

Power from PV (W)

Power to load (W)

Charge in battery(Ah)

Samples per file: 144

Power absorbed by load: 106

Power to load: 105.773

Wiring losses: 10

Power from inverter: 117.526

Inverter Efficiency: 90

Power from battery: 130.584

Figure 4: LabVIEW simulation user interface

Energy stored in the battery is indicated in Ah by firstly converting the incoming power from the charger to Wh. This calculation is shown in Figure 7. LabVIEW has a function that calculates the average value of all the previous samples in the execution of the loop. This average value is then multiplied with the hour value indicated by the total samples in Wh. In the simulation, each sample represents 10 min of the day. Taking the samples from the beginning of the simulation (indicated by the letter i in Figure 7) and dividing it by six results in an hour variable. The amount of energy stored in the battery (24 V) can be calculated by using the energy flowing into the battery and that flowing out to the load (may be controlled by the student). A simple calculation is done by dividing the Wh with the battery voltage to obtain the Ah as shown in Figure 8. The wiring losses are calculated in the same way as the dust and mismatch factor.

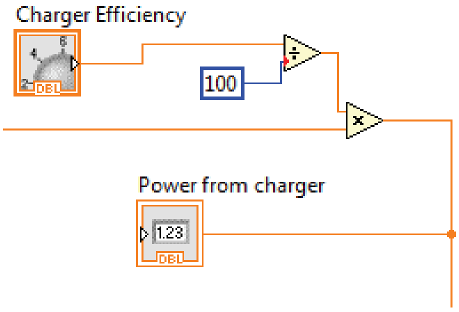


Figure 5: LabVIEW circuit of charge controller

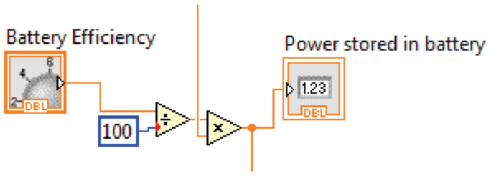


Figure 6: LabVIEW circuit of battery efficiency

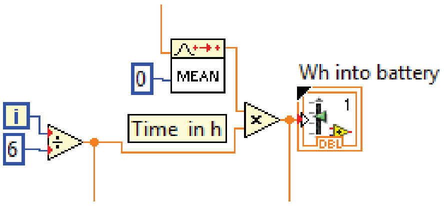


Figure 7: LabVIEW circuit of Wh calculation

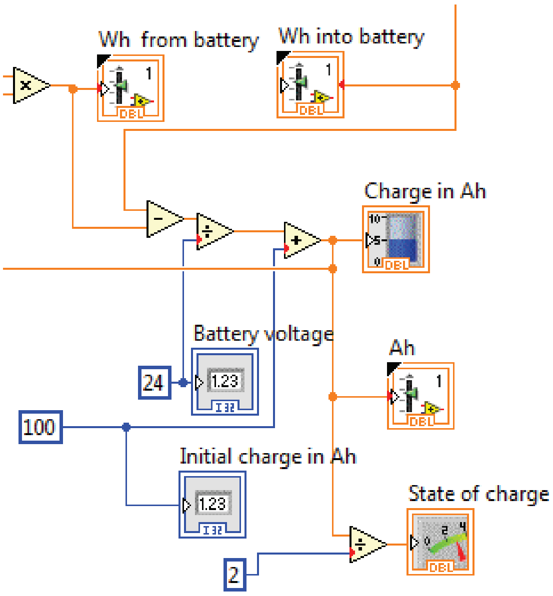


Figure 8: LabVIEW circuit of Ah calculation

The possible results of the simulation are shown in the next section. It highlights the control of the energy source, the different efficiencies and the size of the load.

6. RESULTS AND DISCUSSION

The following important energy monitoring principles are demonstrated with this SEMS:

1. energy flow,
2. efficiency of components in the system,
3. storage of energy,
4. the effect of optimisation and
5. the usage of energy.

Figure 9 illustrates the first principle of energy flow over a 24 hour period. The result shows a constant load (50 W) with normal solar radiation present (bell shaped curve that peeked in this simulation at 14H30). The state of the battery decreases from 100 Ah to around 47 Ah at 11H00, as the constant load is draining the 200 Ah battery. The state of the battery then starts to increase to 185 Ah as solar radiation is present. The 47 Ah point represents 23.5% state of charge (76.5% depth of discharge) that will influence the useful lifetime of the battery. Battery life is influenced by the depth of discharge(DOD), number of cycles, and charge/ discharge rates [28]. Discharging to about 80% DOD will severely reduce the battery life of lead acid batteries[29]. The third principle of energy storage is also demonstrated with this result.

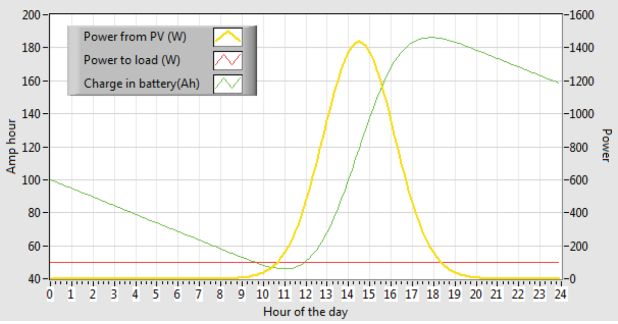


Figure 9: Simulation results of energy flow

The second principle, relating to energy efficiency of the components, is shown in Figure 10. Here, the efficiency of the charge controller was changed from 77 to 84% and the efficiency of the inverter was changed from 89 to 99%. All the other settings, as used in Figure 9, were retained. The result indicates that the state of the battery did not go below 50 Ah and that the battery was fully charged at 16H00. These results also address the principle of optimisation, as higher efficiencies result in a fully charged energy storage system. Fully charged systems can also be an indicator of energy surplus[30].

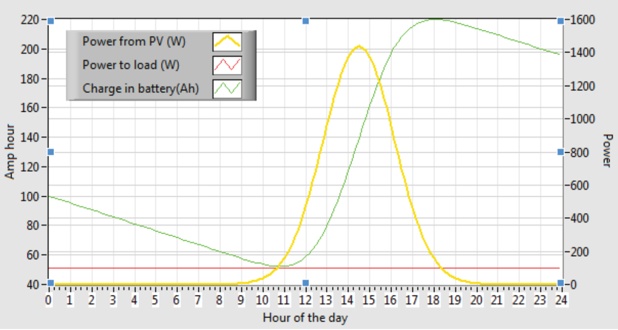


Figure 10: Simulation result of optimization

In order to address the last principal, named energy usage, required using all the settings from Figure 10 in Figure 11, with the exception of the load setting (changed from 100 W to 200 W). The effect of a higher load on the system indicates a 0% state of charge of the battery at 11H00, resulting in a total shutdown on the system. This is an indication of poor design and will result an unusable system[31].

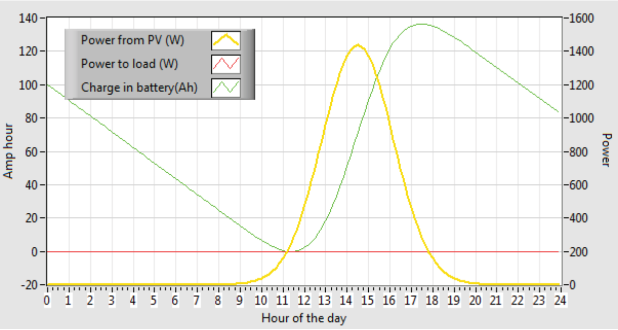


Figure 11: Simulation results with a higher load

Student perceptions are an important indicator to evaluate the success of any educational tool. Three questions were posed to the registered students in the Solar Energy Module at the end of the course (n=10). 90% of the students indicated that they really enjoyed the simulations that were done in the laboratory. Student satisfaction and enjoyment is important in order to maximise learning and to ensure program viability [32]. 80% of the students then indicated that they were able to apply new knowledge in a practical environment by doing the simulations, thereby suggesting that they were able to integrate their theoretical and practical instruction. All the students finally indicated that the simulations were not too difficult, thereby suggesting a good level of difficulty for these engineering students.

7. CONCLUSION

The purpose of this paper was to describe the design of a simulated energy monitoring system (SEMS) that was developed at CUT to help train freshmen engineering students in a renewable energy course. The control of specific parameters in the PV system helped students to conceptualize important energy generation principles, such as electrical energy flow, efficiency, storage, usage and optimisation. Student perspectives revealed student satisfaction with the SEMS. A time lag study may further enhance the reliability and validity of these results, as this study was only limited to one group of students in one semester. However, the call by society for a more sustainable future may very well be achieved by graduating students with the right attributes that may be demonstrated by using specific and relevant CBS.

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9. REFERENCES

[1] BrainyQuote. (2015). *Michael Franti Quotes at BrainyQuote.com*. Available: http://www.brainyquote.com/quotes/quotes/m/michaelfra472140.html

[2] A. Esmat, A. Magdy, W. ElKhattam, and A. M. ElBakly, "A novel Energy Management System using Ant Colony Optimization for micro-grids," in *Electric Power and Energy Conversion Systems (EPECS), 2013 3rd International Conference on*, 2013, pp. 1-6.

[3] N. Perrot, I.-C. Trelea, C. Baudrit, G. Trystram, and P. Bourgine, "Modelling and analysis of complex food systems: state of the art and new trends," *Trends in Food Science & Technology,* vol. 22, pp. 304-314, 2011.

[4] R. Krishnamurthy, A. Bhagwatwar, E. W. Johnston, and K. C. Desouza, "A Glimpse into Policy Informatics: The Case of Participatory Platforms That Generate Synthetic Empathy," *Communications of the Association for Information Systems,* vol. 33, p. 21, 2013.

[5] U. Mohammad, "An Introductory Engineering Course for Freshman Students-From Programming to Implementation," in *ASEE NCS 2014, American Society for Engineering Education*, Oakland University, 2014.

[6] P. E. Hertzog and A. J. Swart, "A customizable energy monitoring system for renewable energy systems," presented at the SAUPEC 2015, University of Johannesburg, 2015.

[7] R. M. Felder and L. K. Silverman, "Learning and teaching styles in engineering education," *Engineering education,* vol. 78, pp. 674-681, 1988.

[8] A. F. Grasha and N. Yangarber-Hicks, "Integrating teaching styles and learning styles with instructional technology," *College Teaching,* vol. 48, pp. 2-10, 2000.

[9] D. I. Lewis, "The pedagogical benefits and pitfalls of virtual tools for teaching and learning laboratory practices in the Biological Sciences," 2014.

[10] E. Cakici and S. Mason, "Parallel machine scheduling subject to auxiliary resource constraints," *Production Planning and Control,* vol. 18, pp. 217-225, 2007.

[11] C.-S. Lam and M.-C. Wong, *Design and Control of Hybrid Active Power Filters*: Springer, 2014.

[12] A. Nechibvute, A. Chawanda, P. Luhanga, and A. R. Akande, "Piezoelectric Energy Harvesting Using Synchronized Switching Techniques," *International Journal of Engineering and Technology,* vol. 2, 2012.

[13] R. Torbensen, K. M. Hansen, and T. S. Hjorth, "My Home is My Bazaar-A Taxonomy and Classification of Current Wireless Home Network Protocols," in *Engineering of Computer Based Systems (ECBS-EERC), 2011 2nd Eastern European Regional Conference on the*, 2011, pp. 35-43.

[14] I. M. Greca, E. Seoane, and I. Arriassecq, "Epistemological issues concerning computer simulations in science and their implications for science education," *Science & Education,* vol. 23, pp. 897-921, 2014.

[15] J. Blackledge and M. Barrett, "Evaluation of a Prototype Desktop Virtual Reality Model Developed to Enhance Electrical Safety and Design in the Built Environment," 2012.

[16] C. P. Casanave and Y. Li, "Novices' Struggles with Conceptual and Theoretical Framing in Writing Dissertations and Papers for Publication," *Publications,* vol. 3, pp. 104-119, 2015.

[17] D. A. Kolb, *Learning Cycle and Learning Style Inventory*. London: Prentice Hall, 1984.

[18] S. Giglmayr, A. C. Brent, P. Gauché, and H. Fechner, "Utility-scale PV power and energy supply outlook for South Africa in 2015," *Renewable Energy,* vol. 83, pp. 779-785, 2015.

[19] T. Sanandaji and P. T. Leeson, "Billionaires," *Industrial and Corporate Change,* vol. 22, pp. 313-337, 2013.

[20] P. Hertzog and A. Swart, "Design and development of practical instruction for freshmen engineering students in a renewable energy course," in *1st International Conference on Scholarship of Teaching and Learning (SoTL) in Higher Education*, Bloemfontein, 2015.

[21] P. Hertzog and A. Swart, "Enhancing freshman engineering student's experiences of photovoltaic module operation using educational technologies," presented at the 11th International Conference on EDUCATIONAL TECHNOLOGIES, Dubai, United Arab Emirates, 2015.

[22] A. Kabade, A. Rajoriya, and U. Chaubey, "Solar Pump Application in Rural Water Supply-A Case Study from Ethiopia," *International Journal of Energy Engineering,* vol. 3, p. 176, 2013.

[23] T. L. Gibson and N. A. Kelly, "Solar photovoltaic charging of lithium-ion batteries," *Journal of Power Sources,* vol. 195, pp. 3928-3932, 2010.

[24] C. Belhadj-Yahya, "Performance monitoring of solar stand alone power systems," in *Energy Conference and Exhibition (EnergyCon), 2010 IEEE International*, 2010, pp. 412-416.

[25] Y. Yao, D. Lu, and D. Verstraete, "Power loss modelling of MOSFET inverter for low-power permanent magnet synchronous motor drive," in *Future Energy Electronics Conference (IFEEC), 2013 1st International*, 2013, pp. 849-854.

[26] S. Ozdemir, U. S. Selamogullari, and O. Elma, "Analyzing the effect of inverter efficiency improvement in wind turbine systems," in *Renewable Energy Research and Application (ICRERA), 2014 International Conference on*, 2014, pp. 572-575.

[27] I. Santiago, M. López-Rodríguez, A. Gil-de-Castro, A. Moreno-Munoz, and J. Luna-Rodríguez, "Energy consumption of audiovisual devices in the residential sector: Economic impact of harmonic losses," *Energy,* vol. 60, pp. 292-301, 2013.

[28] (2 October 2014). Available: http://en.climate-data.org/location/394/

[29] H. Bindner, T. Cronin, P. Lundsager, J. F. Manwell, U. Abdulwahid, and I. Baring-Gould, *Lifetime modelling of lead acid batteries*, 2005.

[30] T. Ma, H. Yang, and L. Lu, "Performance evaluation of a stand-alone photovoltaic system on an isolated island in Hong Kong," *Applied Energy,* vol. 112, pp. 663-672, 2013.

[31] C. L. Khang and Y. C. Liang, "Development of photovoltaic system planning software," in *Sustainable Energy Technologies (ICSET), 2012 IEEE Third International Conference on*, 2012, pp. 200-204.

[32] S. P. Stokes, "Satisfaction of college students with the digital learning environment: Do learners' temperaments make a difference?," *The Internet and Higher Education,* vol. 4, pp. 31-44, 2001.