Abstract—This paper presents a novel automated wind chiller hybrid cooling system applied to a cold storage room. The objective of the new hybrid system is to utilize less electricity from the grid by using a wind chiller setup. The dimensions and cooling load of a typical cold storage room was defined based on the requirements of the Philippine environment. Various cold storage parameters were listed and calculated to fully define the typical cold storage room. An automation system was designed using ladder logic programming to identify the usage of the wind chiller in hybrid with a conventional electric cooling system. The rotational speed of the wind chiller was the primary parameter in accessing the usage of the wind chiller or the electrical cooling system. The automation included lubrication to ensure optimal wind chiller rotation. Equipment for automation implementation were suggested in the study. Simulations showed that the proposed program can control the utilization of wind chiller or the electrical cooling system for optimal performance. Results show that a potential savings of USD 4,860 can be achieved in a year.

Index Terms—wind, chiller, automation, cold storage

I. INTRODUCTION

Philippine electricity is noted to have the third highest power rate in Asia and 16th highest in the world [1]. Aside from the residential sector, the industrial sector also feels the effects of high electricity costs as they take up 27% of the Philippines electricity consumption [2].

Cold storage plants are one of the many industries that are heavily affected by the price of electricity as it can account as much as 50% of the total operating cost [3]. Despite the higher operating cost, cold storage plants are necessary to store the two most common cold storage commodities: meat and fish [4].

The majority of services of a cold storage plant requires a reliable source of power like forced air precooling, individually quick frozen, blast freezing, and walk-in refrigerated cold storage rooms. However, areas without grid connection will find it hard to operate a cold storage plant. Thus, these areas turn to renewable sources of energy to power such services like solar, wind, geothermal, and biomass. With developed technologies behind renewable energy, even grid-tied cold storage plants are considering hybrid systems in order to obtain potential savings during operations [5].

One way to alleviate the excessive consumption of electricity is to integrate wind energy to an existing system or component. In [6], a wind turbine was able to run a compressor used for water cooling. Program Logic Controller (PLC) was used in order to decide when the compressor would run based on the wind turbine rotational speed. A study by Zhao, M. Wang, J. Wang, and Dai [7] implemented simulations of a wind energy hybrid system that involved an adiabatic compressed air energy storage and flywheel energy storage system. Karameldin and Mekhemar [8] simulated wind energy to drive a compressor used for desalination in order to provide potable water in a remote area. The system was coupled to the grid in order to run during low wind speeds. Thermodynamic simulation was done in [9] on a wind turbine hybrid system with advanced adiabatic compressed air energy storage. In their analysis, they were able to point out that the power coefficient of wind turbines affects energy utilization of the system. Wind energy was investigated to power CO$_2$ capture equipment in [10]. Results show that despite wind energy intermittency, the energy requirement of CO$_2$ capture equipment was still met.

Automations in product cooling are beneficial to the operations and profit of a cold storage plant. Usually, an automated facility costs an additional 25-35% higher compared to its conventional counterpart. However, this will lead to approximately 8,000-10,000 or more pallet positions which would generate 50-75% savings in labor costs, 60-80% savings in energy expenditures, and 40-50% less in working footprint [11]. Fig. 1 shows the
energy profile of a typical cold storage plant wherein data came from [12].

It is logical to apply automation to refrigeration for potential savings as it is the major bulk of the energy profile. Automation of individual components of refrigeration system using programmable logic controllers can be used for plant efficiently. Centralized control system can be utilized for ease and accuracy of control. Installation of program controls to compressors of varying capacity to maximize staging efficiency. Controls can even be done to on-off cycles of evaporator fans to reduce evaporator run time. Sensors can be used as a replacement for timed defrost systems which will lead to lesser heat load [12]. This section pre literature regarding automations in product cooling or space cooling.

A freshness gauge was conceptualized by Kim, Aung, and Chang [13] in order to prolong the shelf life and reduce the product loss of perishable goods. In [14], an adaptive algorithm was created in order to control heat sources and cooling ventilation in an office space. Solar thermal energy was used in order to chill water in [15]. They were able to construct a pilot plant wherein automation was done for it to operate fully automatically. A study by van der Sluis [16] simulated a control system and developed to a small scale cold storage space. The goal of their control system is to control the cold store refrigeration compressors in the evening without spoiling the frozen products. Hilton [17] conducted a case study to an Australian cold storage plant on how energy efficiency was improved without an increase in total energy consumption. A controlled smart grid was implemented to a cold storage room in order to utilize renewable energy in [18]. The study used a model predictive control strategy to attain communication flexibility.

From the literature presented, there is a need to utilize hybrid systems in cold storage plants in order to alleviate some burden from the rising prices of electricity and persistent carbon footprint due to the utility of fossil fired power plants. Furthermore, with hybrid systems, the cold storage plants can have control and flexibility in utilizing their existing equipment while being able to save money from such system.

In this study, a new automation setup and hybrid design of a typical cold storage plant was developed. The hybrid design will utilize wind energy while the automation will control the usage over four main equipment namely: wind compressor, wind generator, electrical cooling system, and lubrication unit. This study will provide information for cold storage companies to implement the proposed hybrid system which will include costing, suggested equipment, and ladder logic program. Although such setup will be based on a Philippine environment, other locations can utilize the study's methodology in finding the total cooling load in their respective area.

II. COLD STORAGE PLANT

The automation was done to a typical cold storage plant. Fig. 2 shows the design of the typical cold storage plant. The room has a 15 m x 15 m x 5 m dimension equivalent to 1,125 m³ of cooling volume. The dimensions are estimates based on a real cold storage plant in Quezon City, Philippines.

![Figure 2. Isometric view of the typical cold storage room.](image)

The selected products for cooling will be chicken and tuna. The maintaining temperature in the cold storage plant will be kept at a constant -20°C to prolong the freshness of both products. This is the selected temperature in order to easily achieve the minimum practical storage temperature of meat products at -18°C. At this temperature, chicken will have a prolonged life of 12 months [19] while tuna will have a prolonged life of 4 months [20]. It is assumed that the outside temperature and incoming products will have a temperature of 35.3°C. The highest dry bulb temperature in Luzon island according to the ASHRAE design handbook [21].

In this research, three sources of cooling load will be considered: product load, heat due to wall conduction and convection, and air change load. Adding all cooling loads with a 20% allowance for miscellaneous loads and losses, the total cooling load of the plant is 100.78kW.

III. AUTOMATION CONCEPT AND DESIGN

![Figure 3. Overall flowchart of the automation process.](image)

Fig. 3 shows the overall flowchart of the automation process that will be implemented. Inputs will be fed to the PLC in order to assess the given data. The decision will then be translated into outputs based on the criterion that the PLC has. In order to assess the wind chiller usage, the wind turbine rotational speed will be taken in order to identify when to turn off the electricity compressor and run the wind chiller. Fig. 4 shows the schematic diagram which will determine the wind chiller based on [6].
A. Wind Chiller Automation

Fig. 5 is the intended wind chiller configuration wherein the main shaft is coupled to a compressor and generator based on [6]. Compressors and generators typically require high torque during performance. Thus, a multi-bladed type of wind turbine is recommended because it is capable of producing higher torque compared to the more common three bladed types [22].

Upon activation, the initial source of cooling will be the electricity powered cooling system in order to ensure freshness of the goods inside the room. The criteria to select the wind chiller will start at 80 rpm based on [6]. Lubrication will be implemented to the gears of the wind chiller in order to ensure good rotation of the wind chiller. If the rotational speed is greater than 80 rpm, the cooling system will be turned off in order to run the wind chiller’s compressor for cooling. Below 60 rpm, the compressor will be turned off and the generator will run. Below 40 rpm, the wind chiller will be fully turned off and the electricity powered cooling will be activated once again.

B. Equipment for the Automation

For this system, the recommended PLC to be used is a MicroLogix 1400, an Allen-Bradley compatible device. It can have up to 38 I/O points which is more than enough for the plant setup. When the I/O requirement of the cold storage plant increases, this PLC can be expanded up to seven 1762 I/O modules when needed. Furthermore, it has on-line editing and a built-in LCD panel with backlight. The PLC also has two serial ports and an Ethernet port. Fig. 6 shows the MicroLogix 1400 hardware [23]. With its capability to be used remotely, this PLC does not need to be in the cold storage room when implementing the automation.

To assess the rotational speed of the wind chiller, a ROS-HT tachometer optical sensor will be used shown in Fig. 7. It has a speed range from 1 to 50,000 rpm which is more than enough for the purpose of this research. It can operate from -25°C to 125°C which is durable in outdoor temperatures. It consumes 40 mA of electricity and has a portable size of 73 mm in length and 16 mm in diameter. Fig. 7 shows the photo of the ROS-HT tachometer sensor [24].

For the lubrication pumping, a pump actuator system from Rotork will be used. The pump actuator system is ready for automation. It has a simple design and is standardized for all kinds of power fluids. Furthermore, its pump speed can be adjusted. Fig. 8 shows the image of the Rotork pump actuator [25].

To enable the turning on/off of electricity powered cooling system, wind chiller’s compressor, and wind chiller’s generator, control switches was integrated to all three cooling equipment. These switches will be used by the PLC during its automation. The Rotork pump actuator system will provide lubrication to the main shaft gears. It was also connected to the PLC for manual lubrication option. The wind generator powers the electrical cooling system of the plant when it is enabled. The ROS-HT Tachometer Optical Sensor was used to assess the rotational speed of the main shaft. Data form this device will be used as input to the PLC. Lastly, the PLC determined the use of either the wind compressor, wind generator or the electrical cooling system to cool the cold storage room.
IV. PROGRAMMING

This research makes use of PicoSoft v6.22 to simulate the automation process. This software version was able to demonstrate the ladder logic behind the automation of the system. Table 1 shows all programming elements used while Fig. 9 is the ladder logic of the automation system.

<table>
<thead>
<tr>
<th>Element</th>
<th>Representation and Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Basic Units</td>
<td></td>
</tr>
<tr>
<td>I01</td>
<td>On Button</td>
</tr>
<tr>
<td>I02</td>
<td>Off Button</td>
</tr>
<tr>
<td>I03</td>
<td>Rotational Speed is 80 rpm or more</td>
</tr>
<tr>
<td>I04</td>
<td>Rotational Speed is 60 to 80 rpm</td>
</tr>
<tr>
<td>I05</td>
<td>Rotational Speed is 40 to 60 rpm</td>
</tr>
<tr>
<td>I06</td>
<td>Rotational Speed is 0 to 40 rpm</td>
</tr>
<tr>
<td>Output Basic Units</td>
<td></td>
</tr>
<tr>
<td>Q01</td>
<td>Automation System is On</td>
</tr>
<tr>
<td>Q02</td>
<td>Electricity Cooling System is On</td>
</tr>
<tr>
<td>Q03</td>
<td>Wind Compressor is On</td>
</tr>
<tr>
<td>Q04</td>
<td>Wind Generator is On</td>
</tr>
<tr>
<td>Q05</td>
<td>Lubrication is being Applied</td>
</tr>
<tr>
<td>Markers</td>
<td></td>
</tr>
<tr>
<td>M01</td>
<td>Initiate System Start-up</td>
</tr>
<tr>
<td>M02</td>
<td>Electric Cooling System Usage</td>
</tr>
<tr>
<td>M03</td>
<td>Wind Compressor Usage</td>
</tr>
<tr>
<td>M04</td>
<td>Wind Generator Usage</td>
</tr>
<tr>
<td>M05</td>
<td>Lubrication Usage</td>
</tr>
<tr>
<td>Timing Relays</td>
<td></td>
</tr>
<tr>
<td>T01</td>
<td>Two second Application of Lubrication</td>
</tr>
</tbody>
</table>

The wind selection automation will start with I01 which will turn on the system. This will make all remaining inputs either partially or fully activated. Cooling system will be initially turned on to ensure freshness of goods upon starting.

I02 is the off button which can be applied as long as the system is on. This can be used during any stage of the automation as it will reset all equipment used. I03 can be activated only when the system is on and the electric cooling system is on. When the wind turbine rotation reaches 80 rpm, it will turn off the electric cooling system and enable the wind compressor to power cooling. Lubrication is automatically applied in order to ensure longer rotation form the wind turbine. I04 can be activated only when the system is on and the wind compressor is on. This is the condition in order to avoid initially starting the wind compressor within the 60-80 rpm range. This will activate the same marker with I03 which is M03.

I05 can be activated only when the system is on and the wind compressor is on. This input will turn off the wind compressor and activate the wind generator. I06 can be activated only when the system is on and the wind generator is on. This input will turn off the wind generator and turn on the electric cooling system. Lubrication can be activated manually even though the automation system is not activated in order to provide flexible lubrication to the users.

Figure 9. Circuit diagram of the automation
V. RESULTS

Fig. 10 shows a sample the programming circuit under simulation. It shows the usage of the wind generator. I06 can be utilized since Q04 is active. Upon activating I06, the simulation will go back to its original state. The electrical cooling system will be used again.

To assess the economic viability of the whole automation, costing will be investigated. Table 2 shows the estimated cost of the whole automation setup. Wind chiller setup and Rotork pumping actuator systems were rough estimates based on the author’s experience. The pricing for the MicroLogix 1400 and ROS-HT came from [26] and [27] respectively. Communication and Electric Cables, Other Incidental Material Expenses, and Labor and Supervision Cost came from [28] for the rough estimation.

<table>
<thead>
<tr>
<th>Equipment/Expenses</th>
<th>Cost (in Php)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Chiller Setup</td>
<td>1,000,000</td>
</tr>
<tr>
<td>MicroLogix 1400</td>
<td>18,000</td>
</tr>
<tr>
<td>ROS-HT</td>
<td>15,000</td>
</tr>
<tr>
<td>Rotork Pumping Actuator System</td>
<td>50,000</td>
</tr>
<tr>
<td>Communication and Electrical Cables</td>
<td>5,000</td>
</tr>
<tr>
<td>Other Incidental Material Expenses</td>
<td>5,000</td>
</tr>
<tr>
<td>Labor and Supervision Cost (144 man-hours)</td>
<td>12,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,105,000</strong></td>
</tr>
</tbody>
</table>

Equation (1) shows how to compute ordinary annuity given present value, interest, and time period from [29]. If the money to pay the full system is borrowed, the yearly cost of this debt is approximately equal to Php 227,000 (around USD 4,550). This is assuming a 10% interest, over a seven year period.

\[
R = PV \left[ \frac{i}{1-(1+i)^{-n}} \right] \tag{1}
\]

where:
- \( R \) – ordinary annuity, Php
- \( PV \) – present value, Php
- \( i \) – interest in decimal form
- \( n \) – number of years

From [6], the wind chiller is able to produce 0.778 kW of cooling in a span of five hours. Using ratio and proportion, it is assumed that the wind chiller is capable of cooling 3.73 kW of heat in a 24 hour span. Therefore, for one wind chiller, it is responsible for using 3.70% of the total cooling load of the cold storage room. The electricity price in Metro Manila cost Php 7.42/kWh [30]. Thus, 3.73 kW generated translates to a Php 664.24 of savings in a day or a Php 242,447 (around USD 4,860) in a year. Since the annualized cost of the whole automation is less than the savings the wind chiller can supply, it is economically feasible to utilize wind chiller as partial load for a payback period of seven years.
VI. CONCLUSION

A novel hybrid cooling automation system for a typical cold storage room application in Philippine conditions was considered. The typical cold storage plant was defined by listing various parameters including room dimensions, indoor temperature, outdoor temperature, and products to be cooled. Three sources of cooling load were considered, namely product load, wall heating load, and air change load. A 20% allowance was included for miscellaneous loads.

The goal of the automation is to utilize less electricity from the grid to cool the cold storage room. This can be achieved by utilizing the wind chiller when sufficient wind speed is felt. A circuit diagram was made in order to decide wind chiller activation as replacement of the electrical cooling system. The main factor for the wind chiller utilization was the shaft’s rotational speed. Lubrication was also included in the automation for flexible lubrication and smoother rotation.

The ladder logic program was simulated in a PLC software. Results showed that the program was able to respond to all Input Basic Unit and provided the intended Output Basic Unit. Costing was done to assess the economic feasibility of the whole setup. Results showed that implementing the wind chiller automation integration is economically feasible since the annualized cost of USD 4,550 from construction is less than the potential earnings of USD 4,860. Suggestion for future research would include feasibility of using solar energy or other renewable energy sources instead of a wind generator.

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