The Canadian Society for Bioengineering
The Canadian society for engineering in agricultural, food, environmental, and biological systems.

La Société Canadienne de Génie Agroalimentaire et de Bioingénierie
La société canadienne de génie agroalimentaire, de la bioingénierie et de l'environnement

CSBE | SCGAB

Paper No. CSBE18-109

Grain Drying Utilizing Air Source Heat Pumps for Reduced Cost and Greenhouse Gas Emissions

Adam Epstein, William Lubitz

School of Engineering, University of Guelph. Guelph, ON, Canada. N1G 2W1.

Greg Dineen

APS Dineen Farms, Kenilworth, ON, Canada. N0G 2E0

James Dyck

Ontario Ministry of Agriculture, Food and Rural Affairs, Vineland Station, ON, Canada. L0R 2E0.

Written for presentation at the
CSBE/SCGAB 2018 Annual Conference
University of Guelph, Guelph, ON
22-25 July 2018

ABSTRACT Grain must be dried at the end of the season so that it can either be sold or safely stored. Grain drying is one of the most energy intensive agricultural activities. Drying is commonly done in Canada using high temperature, propane-fueled driers. Alternatives include low temperature or ambient air drying. Electrically-powered air source heat pumps are a promising source of heat for low temperature drying. Prior literature and preliminary results suggest grain drying incorporating heat pumps may be cost-competitive with conventional propane dryers while having far lower greenhouse gas (GHG) emissions, particularly in many parts of Canada where electricity is mainly supplied by low-GHG intensity sources like hydro and nuclear. Experimental drying data were collected at a farm in Southern Ontario during the 2016 and 2017 growing seasons. Drying trials were completed for corn, soybeans, and rye stored in a conventional vertical grain bin. A standard ventilation fan was used to move air through the grain, either at ambient conditions, heated electrically, or using a prototype air supply system that includes an air-source heat pump. Efficiencies of conventional drying systems will be reported from previous papers and compared to potential efficiencies of a heat pump-based system. This study will also discuss grain drying rates and estimated costs for heat pump drying systems.

Keywords: Grain drying, heat pump, experiment, drying time, moisture.

INTRODUCTION Energy for drying is one of the largest costs associated with grain production. The majority of grain drying in Ontario, Canada is done by high temperature propane-fueled dryers. Alternatives include low temperature and natural air drying. This paper provides a review of existing grain drying knowledge and models and includes consideration of using an air source heat pump as a heat source for low temperature drying in grain bins. Low temperature drying experimental data collected during the 2017 harvest season is presented.

BACKGROUND

Conventional Drying Methods Grain drying can be done on-farm or at the grain elevator using high temperature air, low temperature air, or ambient air. The most common method is high temperature drying, with drying temperatures typically above 50°C. For low temperature drying, air is heated 2°C to 5°C. After drying, grain must be cooled to below 25°C (McFarlane & Bruce, 1996). Hellevang (1987) found that to remove one kilogram (2.2 pounds) of water requires 0.64 to 0.77 kWh (1000 to 1200 BTU) for natural air drying, 0.77 to 0.97 kWh (1200 to 1500 BTU) for low temperature drying, and 1.16 to 1.94 kWh (1800 to 3000 BTU) for high temperature depending if air recirculation is used. Combination drying involves drying corn in a high temperature dryer until approximately 20% moisture content followed by cooling and drying to the final moisture content. Combination drying required 1.14 kWh per kilogram of water removed compared to 1.07 kWh per kilogram and 1.11 kWh per kilogram for low and high temperature drying, respectively (Otten & Brown, 1982). Dryer energy usage can be decreased by 20% to 40% through the use of heat exchangers or recirculation of air leaving the dryer (Dyck, 2017). The trade-off with recirculating the warm air is an increase in drying time due to the higher moisture content compared to the ambient air.

Brown et al (1979) found that low temperature drying produced higher quality corn compared to high temperature drying and high temperature dryeration. Dryeration requires drying the grain until it reaches 2% to 3% above the target moisture content, followed by steeping in an intermediate bin to equalize the moisture content. Finally, a fan cools the grain and dries to the desired level (Dyck, 2017). High temperature drying resulted in greater occurrence of stress cracking regardless of the drying method (Brown, Fulford, Daynard, Meiering, & Otten, 1979).

Moisture Distribution Bakker-Arkema (1997) found moisture content of grain prior to drying was normally distributed, with a higher standard deviation for increasing moisture content. The grain output from a cross flow dryer had larger variability in moisture content due to inconsistent drying. Typical harvest in Ontario yields corn at around 25% moisture although some years it can be much greater (Otten & Brown, 1982).

Grain Drying Models Many different grain drying models have been proposed, typically based on a heat and mass balance of air and moisture through the grain. The grain is assumed to reach an equivalent moisture content (EMC) with the air. The EMC is based on the grain moisture content and temperature and relative humidity of the air. Most models assume constant moisture content throughout the grain prior to drying although Bakker-Arkema (1997) found large variability in the moisture distribution.

Grain drying models are either equilibrium, non-equilibrium, or logarithmic. Equilibrium models assume equilibrium conditions exist between the drying air and grain. A grain drying model based on the assumption that the energy loss of the air flowing through the grain is equal to the energy required to evaporate the moisture leads to a logarithmic relationship. A comparison between equilibrium and logarithmic models found that both models slightly overestimated drying times and diverged at large temperature differences (Lopes, Steidle Neto, & Santiago, 2014).

Dryer Control Methods Grain must be dried below required moisture thresholds to ensure stability in storage. Dryer control methods are an important aspect of ensuring dried grain is below the storage moisture threshold while avoiding overdrying or excess energy usage. Overdrying of grain wastes energy and increases costs, while reducing the grain quality. McFarlane and Bruce (1996) proposed a control method for a continuous flow dryer that was based on calculation of cost due to thermal damage to grain, fuel cost, output moisture content, cooling of heated grain, and time to dry. The control method reduced simulated drying time by 18% and simulated cost by $0.52 (0.30£) per tonne dried, however implementation of the controller on an actual dryer was not discussed.

Heat Pumps Air source heat pumps use electricity to power a refrigeration cycle that transfers heat extracted from ambient air to the air flowing into the drying system. The coefficient of performance (COP) of the heat pump is the ratio of heat transferred to the air divided by the electrical energy input. Heat pumps COPs used for drying typically range from 3 to 5 (Colak & Hepbasli, 2009). Early investigation into heat pumps for grain drying found it not to be economical due to low fossil fuel prices in the 1970s (Hogan, et al., 1983). Lifecycle cost analysis found that heat pumps are economical to dry grain in South Africa from 18% to 15% only if operating for a minimum of three months per year, which is less than the typical drying period in South Africa (Meyer & Greyvenstein, 1992). Due to the low carbon intensity of the Ontario power grid, heat pumps for grain drying can be used to reduce the greenhouse gas emissions compared to propane or natural gas fueled drying.

METHODS

Measurement Campaign During the 2016 and 2017 harvest seasons, drying data was collected at a farm in southwestern Ontario for soybeans and corn. This paper focuses on one trial where an 8 m (27 feet) diameter bin was filled with corn at approximately 34.5% initial moisture content to a depth of 1.1 metres (44 inches), equal to approximately 35,000 kg. Sensors were positioned throughout the bin to measure temperature and relative humidity. The trial began on November 25, 2017 at 02:18 PM (experiment time 0) and ran until December 06, 2017 at 09:13 PM. Midnight is indicated as a vertical line on all figures and the heating load is shown as a gray bar plot in the background.

A fan is used to move air which has been pre-warmed through the bin. Air enters through a single duct at the base of the bin into an open plenum space below the grain. The grain volume rests on a perforated floor. Air flows upward through the grain volume and exits the bin through roof vents. Moisture content of the corn was measured every two days by taking samples at depths of 0.12 metre (5 inch) increments to the moisture analyzer at the local grain elevator. Thermocouples (Type E) connected to a Campbell Scientific CR1000 data logger were placed at multiple heights at two different locations in the grain to measure temperature in five-minute intervals, shown in Figure 1. Additional sensors with integrated dataloggers (EL-USB-2-LCD+) measured relative humidity and temperature of the ambient air, the air in the lower plenum of the bin after being heated, and the air leaving the grain volume in the upper plenum, at one-minute intervals.

Seven electric resistance heaters, each rated at 4.8 kW, were used to heat the incoming air. Electricity usage was metered, allowing accurate tracking of the amount of energy input to the incoming air. The number of heaters in operation varied throughout the trial to adjust for the weather forecast. Electric heaters were used as the low temperature heat source to achieve consistent heating which resulted in benchmark data for low temperature drying. A second trial that is not reported here used a heat pump as the heat source was able to provide 26.6 kW of heat using 3.84 kW of electricity, resulting in a COP of 6.93.

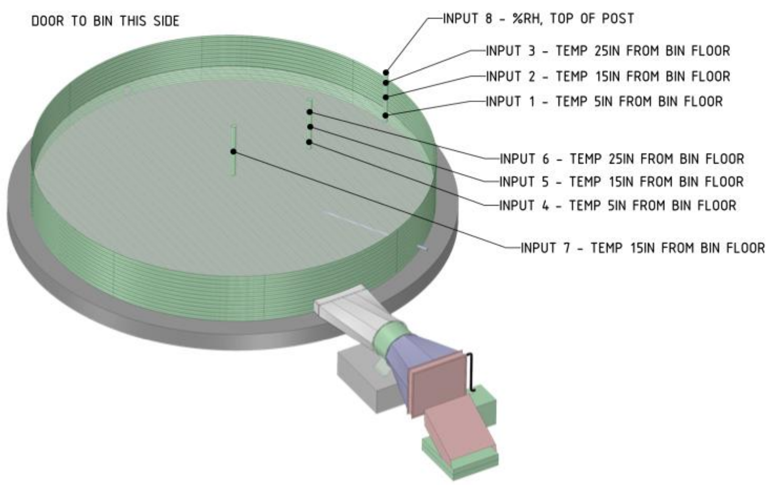

Figure 1. Experiment bin overview showing location of thermocouples within grain volume.

RESULTS

The measured moisture content is shown in Figure 2. Drying occurred within the first five inches within the first interval. By the sixth day, the drying layer had progressed up to 20 inches, with the first 10 inches approaching the desired 15% moisture content. There are fluctuations in the moisture content of the wet layers that could be due to error in measurement, rewetting of the upper layers as the drying air saturates, and uneven moisture distribution in the grain as found by (Liu, Montross, & Bakker-Arkema, 1997).

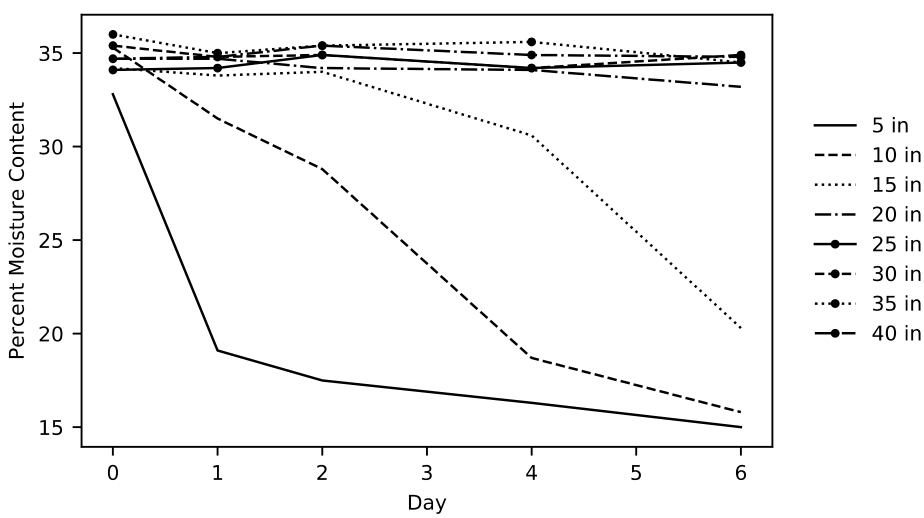

Figure 2. Measured grain moisture content at 0.12 m (5 inch) depth intervals within the grain volume.

USB datalogger temperatures are shown in Figure 3. The two sensors in the lower plenum were consistent for both temperature and humidity (Figure 5). The temperature difference between the inlet and heated air remained relatively constant for a constant heating load. The temperature of the air in the upper plenum of the bin is affected much less by the changing air inlet conditions. Around hour 72, there are drops in the lower plenum values of unknown origin. The air leaving the grain is warmer than the inlet air, which means there is the potential for heat recovery or recirculation of the air, although approaching saturation (Figure 5).

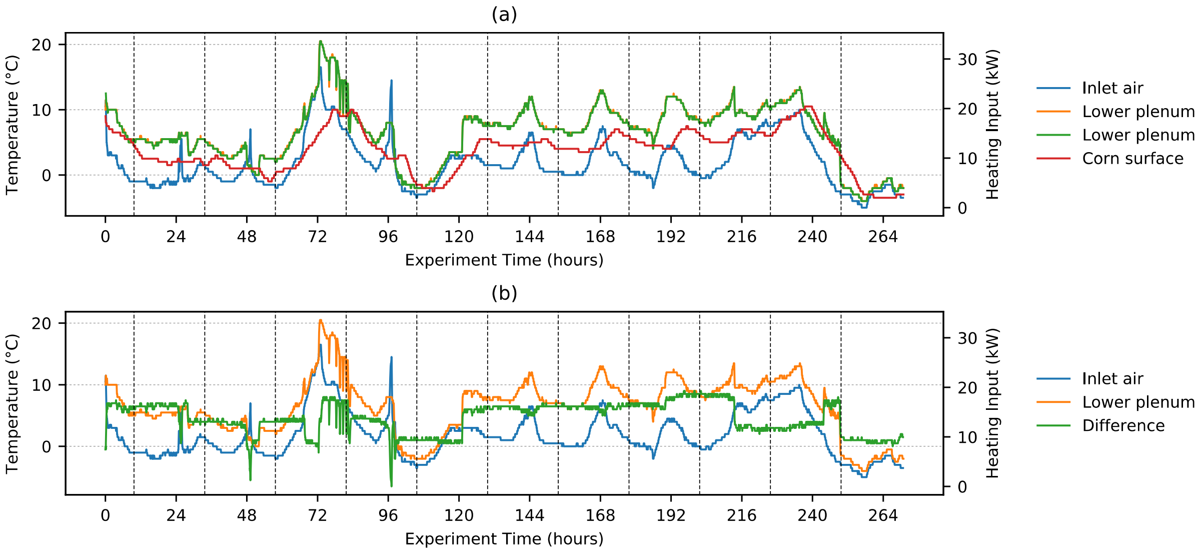

Figure 3. (a) Temperature measurements of ambient inlet air, heated air in the lower plenum, and corn surface. (b) Temperature difference between ambient and heated air.

Grain temperatures are presented in Figure 4 at heights within the grain volume of 12.7 cm, 38.1 cm and 63.5 cm (five, fifteen, and twenty-five inches for the inner tube and outer tube, and at fifteen inches for the center, inner, and outer tubes). Initially, temperatures at all three heights are similar. It is apparent that the outer ring was heated at a faster rate than the inner ring. The temperature at fifteen inches diverges from the 25-inch temperature around hour 100 for the outer ring, but not

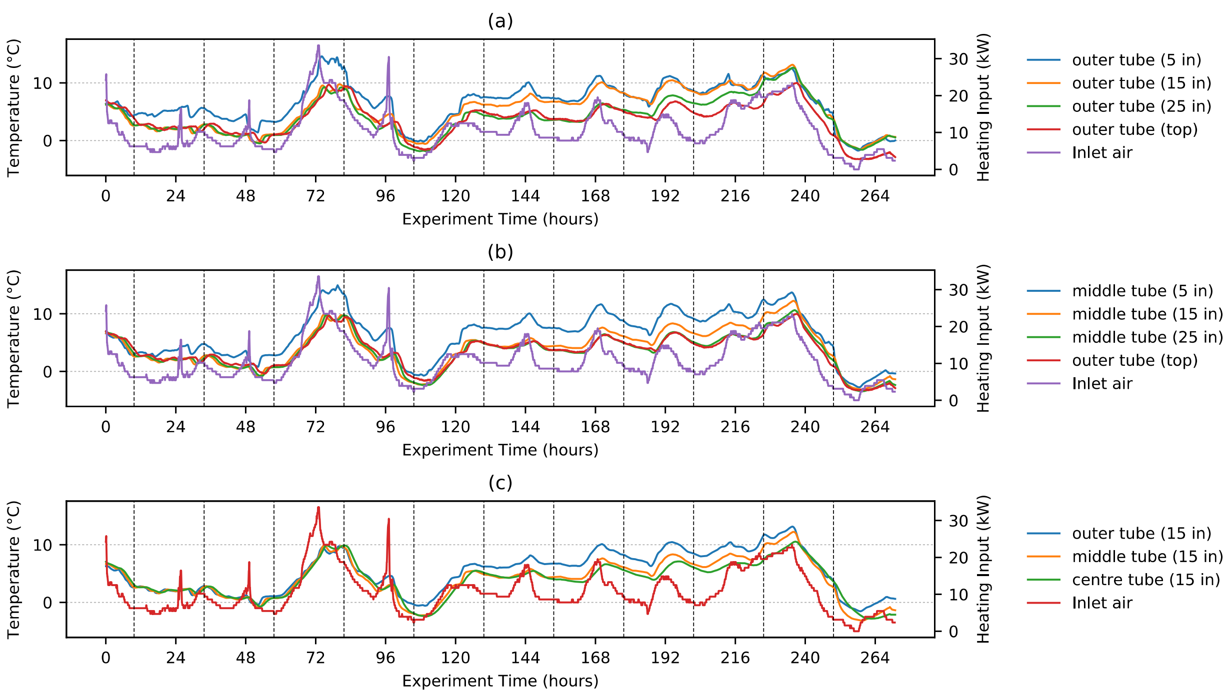

Figure 4. Temperature measurements at depths of 12.7 cm, 38.1 cm and 63.5 cm corn depth for (a) the outer tube and (b) the middle tube. Temperature measurements (c) at 38.1 cm corn depth at the outer, middle, and centre tubes.

until around hour 150 for the inner ring. It is suspected that the difference in warming is due to uneven airflow through the grain.

The ambient air was often above 80% relative humidity (Figure 5). By heating the air as little as 5°C, the humidity drops to below 60%, greatly improving the drying potential of the air.

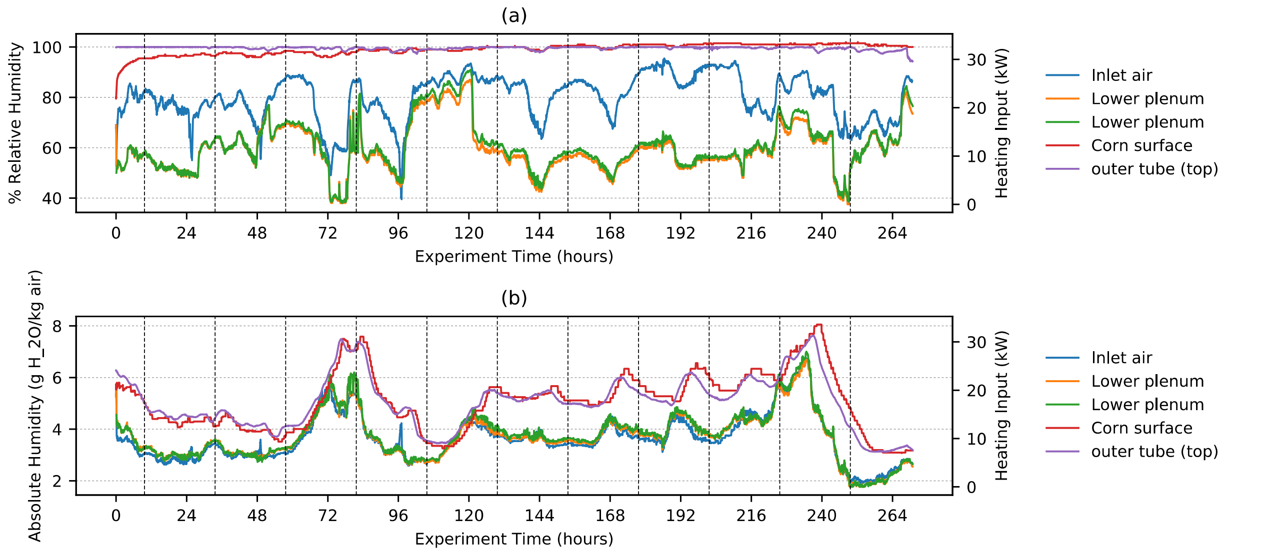

Figure 5. (a) Relative and (b) absolute humidity measurements of ambient air, heated air, and air leaving the grain.

The heat loss of the air as it flows through the grain (Figure 6) confirms that the outer layer of the bin is heated faster than the inner layer. Heat transfer to the outer layer is apparent immediately, while the inner layer does not begin to dry until twelve hours after the trial began.

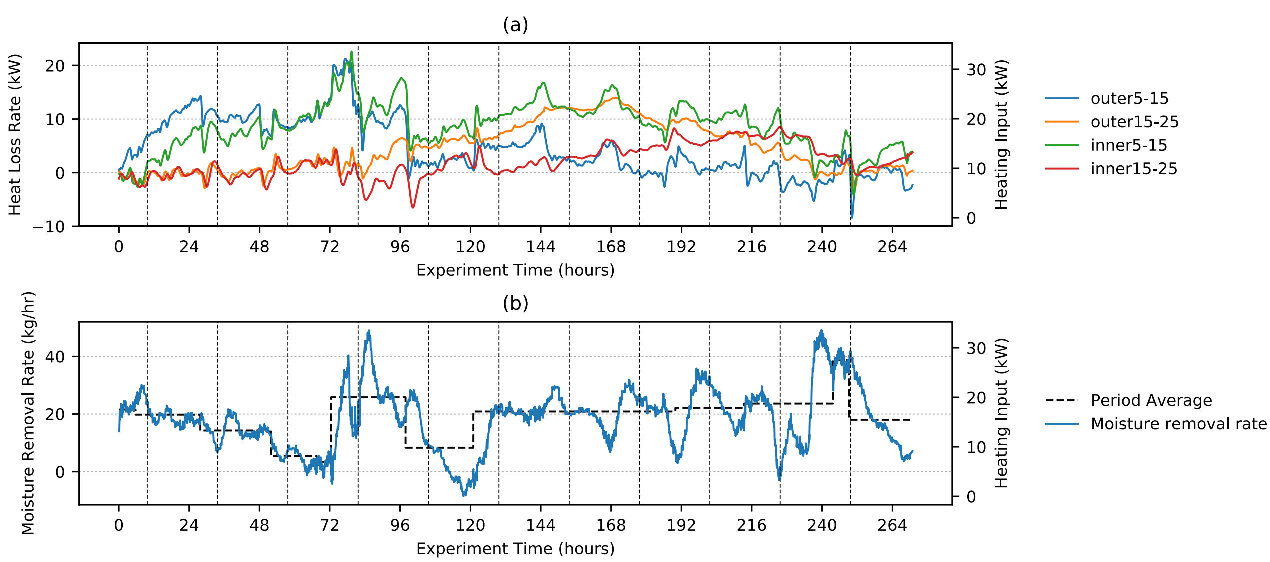

Figure 6. (a) Heat loss in air as it flows through the grain from 12.7 cm to 38.1 cm and 38,1 to 63.5 cm. (b) Rate of moisture removal rate.

The moisture removal rate, calculated by the change in absolute humidity of the air before and after the grain, varies with the heating load and time of day. When the heating load is changed there is a noticeable response time. When the heat source for the air was turned off, the drying rate slowly decreased, eventually falling below zero around hour 120. This shows that the ambient air, during this trial in November, is not sufficient to dry corn.

Energy Analysis From hour 120 to hour 192, a constant heat load of 14.4 kW was applied to the air and the fan power was 2.2 kW (3 hp). During this time, the temperature of the air was warmed by an average of 6°C and the average moisture removal rate was 22 kilograms of water per hour. The energy required to remove one kilogram of moisture from the corn was 0.75 kWh, which is slightly lower than the energy requirement of 0.77 to 0.97 kWh from Hellevang (1987) and lower than the energy requirement of 1.07 kWh from Otten (1982). To reduce the moisture content of 35,000 kg of corn from 34.5% to 15%, 8,029 kilograms of water must be removed. Based on the observed drying rate, this corresponds to 365 hours of drying, requiring 5,256 kWh of heat input and 803 kWh for the fan.

The experimental COP of 6.93 was higher than the typical range of COP (3 to 5) for heat pump drying (Colak & Hepbasli, 2009). A heat pump with a COP of 6, in between the reported and experimental values, would be able to provide the required heating load to remove the 8,029 kg of moisture with 876 kWh of electricity. Based on the carbon intensity of the Ontario electricity grid of 0.053 kilograms of CO_2e per kWh (Intrinsik Corp., 2016) this would result in emissions of 89 kg of CO_2e. Electric heating would require the full 5,256 kWh to be supplied from electricity resulting in emissions of 321 kg of CO_2e. Comparison of low temperature drying using electric heaters and a heat pump and high temperature drying using propane and natural gas are shown in Table 1.

Table 1. Comparison of energy, cost, and GHG of different drying methods to remove 8029 kg moisture

	Electric Heaters	Heat Pump	Natural Gas	Propane
Drying Temperature	Low	Low	High	High
Energy Input (kWh)[1]	6,059	1,679	9,314 - 15,577	9,314 - 15,577
Carbon Intensity[2] (g CO_2e/kWh)	53	53	181	215
Total emissions (kg CO_2e)	321	89	1,686 - 2,819	2,003 - 3,349
Fuel Cost[3] ($/kWh)	$0.12	$ 0.12	$0.032	$0.049
Total Cost	$727	$201	$295 - $493	$453 - $757

1. Fan energy including in heating input for high temperature drying (based on values reported by Hellevang 1987). For low temperature drying, fan input is 748 kWh.
2. (U.S. Energy Information Administration, 2018)
3. (Ministry of Energy, Northern Development and Mines, 2018)

CONCLUSION The experimental data collected during the 2017 harvest season demonstrates the potential effectiveness of low temperature drying in Ontario to reduce cost and greenhouse gas emissions. Natural air drying late in the harvest season can lead to rewetting of the corn. Significant drying can be realized by raising the temperature of the incoming air as little as 5°C. Using a heat pump to condition incoming air for low temperature drying should have reduced operating costs compared to using electrical heaters or high temperature propane drying and is comparable to high temperature drying with propane, while GHG emissions are significantly reduced. Temperature measurements in the bin demonstrated that the drying is not one dimensional and conditions within the grain at different locations in a bin can be variable.

REFERENCES

Best, R., Cruz, J. M., Gutierrez, J., & Soto, W. (1996). Experimental results of a solar assisted heat pump rice drying system. *Renewable Energy, 9*(1-4), 690-694.

Brown, R., Fulford, G., Daynard, T., Meiering, A., & Otten, L. (1979). Effect of drying method on grain corn quality. *Cereal Chemistry, 56*(6), 529-532.

Colak, N., & Hepbasli, A. (2009). A review of heat pump drying: Part 1 - Systems, models and studies. *Energy Conversion and Management, 50*(9), 2180-2186.

Dyck, J. (2017). *Reducing energy use in grain dryers.* OMAFRA Factsheet 17-001.

Hogan, M., Ayers, D., Muller, R., Foster, G., Rall, E., & Doering, O. (1983). Heat pump for low-temperature grain drying. *Transactions of the ASAE, 26*(4), 1234-1238.

Intrinsik Corp. (2016). *Greenhouse gas emissions associated with various methods of power generation in Ontario.* Technical Report prepared for OPG, Project # 20-22285, Mississauga.

Liu, Q., Montross, M., & Bakker-Arkema, F. (1997). Stochastic modelling of grain drying: Part 1. Experimental investigation. *Journal of Agricultural and Engineering Research, 66*(4), 267-273.

Lopes, D., Steidle Neto, A., & Santiago, J. (2014). Comparison of equilibrium and logarithmic models for grain drying. *Biosystems Engineering, 118*, 105-114.

McFarlane, N., & Bruce, D. (1996). A cost function for continuous-flow grain drying and its use in control. *Journal of Engineering Research, 65*(1), 63-75.

Meyer, J. P., & Greyvenstein, G. P. (1992). The drying of grain with heat pumps in South Africa: a techno-economic analysis. *International Journal of Energy Research, 16*(1), 13-20.

Ministry of Energy, Northern Development and Mines. (2018). *Module 4: Fuels system Cost Outlook*. Retrieved from Fuels Technical Report: https://www.ontario.ca/document/fuels-technical-report/module-4-fuels-system-cost-outlook

Otten, L., & Brown, R. B. (1982). Low-temperature and combination corn drying in Ontario. *Canadian Agricultural Engineering, 24*(1), 51-55.

U.S. Energy Information Administration. (2018). *How much carbon dioxide is produced when different fuels are burned?* Retrieved from https://www.eia.gov/tools/faqs/faq.php?id=73&t=11