

Impact Assessment of Energy Conservation Strategies in Swine Barns
through Benchmarking and Building Simulation

A Thesis Submitted to the College of
Graduate Studies and Research

In Partial Fulfillment of the Requirements

For the Degree of Master of Science

In the Department of Agricultural and Bioresource Engineering

University of Saskatchewan

Saskatoon

By

Eleonor Cabrera Navia

© Copyright Eleonor Cabrera Navia, November, 2008. All rights reserved.

PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

Requests for permission to copy or to make other use of material in this thesis in whole or part should be addressed to:

Head of the Department of Agricultural and Bioresource Engineering

University of Saskatchewan

Saskatoon, Saskatchewan S7N 5A9

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my supervisor, Dr. Bernardo Predicala, for all the guidance and support throughout the course of my program. Financial assistance provided by the Advancing Canadian Agriculture and Agri-Food Saskatchewan is also acknowledged. I also want to thank my graduate advisory committee members, Dr. Oon-Doo Baik and Dr. Huiqing Guo, for their valuable comments and suggestions. Thank you to Dr. Satya Panigrahi and Dr. David Torvi who respectively serve as the chairman and external examiner during my defense. I am also indebted to my previous supervisors who encouraged me to pursue this program particularly Dr. Arsenio Resurreccion, Dr. Arnold Elepaño, Dr. Jun Custodio, Prof. Jimmy Williams, Engr. Darwin Aranguren and Engr. Romeo Eusebio. I would like to extend my appreciation to all the barn and office staff at Prairie Swine Center Inc. especially Edie, Donna, Rob, John, Ken, Lee, Emmanuel and Zhifang. I am grateful to Daisy Asis and Anton Siaotong for their advices and encouragement.

Life as a student in a foreign country and away from my family is tough but I was able to pull it through with the help of my friends. For this, I am eternally grateful to Daisy and Joy; Nena, Onil, Lois and Lindey Villaruz; Bob, Ann and David Richards. I also want to thank Mico and Beauty who were always there for me despite the distance. I would like to thank Kuya Roel Kuya Rico, Tito Cesar, Tito Nick, Tita Myr and their families for all the love and encouragement they had provided me through the years. I am forever thankful to Tito Archie, Tita Emma and Dianne Perio for their unending support and unconditional love. Above all, I would like to thank God for giving me the wisdom and strength to complete my M.Sc. program.

To Tatay Bert, Nanay Elvie and Lola Fely

ABSTRACT

Energy input is vital in every swine operation as it directly affects production performance and overall profitability. With the increasing trend in energy prices and feed costs, the swine industry needed to find ways to improve energy use efficiency in their operations in order to reduce overall cost of production. The goals of this study were to gather benchmark information on current energy usage in swine barns through survey and energy audit, and evaluate different energy-saving measures through building simulation.

The results of the survey showed that the average electricity and gas cost was \$6.50/head for farrow-to-finish barns, \$1.70/head for grow-finish barns, \$0.59/head for nursery and \$1.95/head for farrow-wean barns. Significant difference ($P < 0.05$) in energy usage within the same type of operation was observed, implying significant opportunities to improve energy use practices in some barns to reduce overall energy costs.

The results of the barn monitoring showed that the average daily electricity consumption during summer for farrowing, nursery, grow-finish and gestation room was 3.79 kWh/head (16 sows); 0.12 kWh/head (226 pigs); 0.14 kWh/head (551 pigs) and 0.33 kWh/head (349 sows); respectively. During winter, the average daily electricity consumption for farrowing, nursery, grow-finish and gestation room was 3.92 kWh/head (15 sows); 0.14 kWh/head (227 pigs); 0.09 kWh/head (521 pigs) and 0.22 kWh/head (322 sows); respectively. Highly negative correlation (range from -0.6 to -0.9) was observed between the fan energy consumption and gas concentration of H_2S , NH_3 and CO_2 during summer. This implied that reducing ventilation rate was not a sound option to reduce energy consumption.

A simulation model was developed using the principle of heat transfer and thermodynamics to evaluate various energy-conservation measures through building simulation. Applying energy conservation strategies to lighting, creep heating, recirculation fans, exhaust fans, feed motor and heat recovery, an average annual savings of 25,957 kWh (43 kWh/sow); 47,391 kWh (79 kWh/sow); 9,872 kWh (16 kWh/sow); 118,890 kWh (198 kWh/sow); 1,846 kWh (3 kWh/sow); and 74,952 m³ (125 m³/sow) can be achieved, respectively. The outcome of this research project will help pork producers in managing the use of energy in their operations more efficiently, thereby reducing overall energy costs. Additionally, the reduction of energy use across the industry would contribute to the reduction in greenhouse gas emissions associated with energy generation.

TABLE OF CONTENTS

PERMISSION TO USE	i
ACKNOWLEDGEMENT	ii
ABSTRACT	iv
TABLE OF CONTENTS	vi
LIST OF FIGURES	xiii
NOTATION	xv
1 INTRODUCTION	1
2 OBJECTIVES	5
3 LITERATURE REVIEW	6
3.1 Uses of Energy in Swine Barns	6
3.1.1 Creep heating	7
3.1.2 Space heating	7
3.1.3 Lighting	8
3.1.4 Ventilation	9
3.1.5 Feed and manure handling	11
3.2 Indoor Air Quality Measurement (IAQ)	11
3.3 Studies on Energy Consumption in Swine Barns	13
3.4 Studies on Energy Conservation Strategies in Swine Barns	15
3.5 Studies on Building Simulation	17
3.6 Research Studies Needed	19
4 DETERMINATION OF ENERGY USE THROUGH BENCHMARKING	21
4.1 Introduction	21
4.2 Materials and Methods	22
4.2.1 Energy survey	22
4.2.1.1 Development of the survey questionnaire	22
4.2.1.2 Sampling method and distribution of questionnaire	23
4.2.1.3 Analysis of the survey results	23
4.2.2 Barn Monitoring	24
4.2.2.1 Instrumentation	26

4.2.2.2	Measurement of Electrical Energy Consumption	27
4.2.2.3	Measurement of Indoor Air Quality Parameters.....	28
4.2.2.4	Measurement of Natural/Propane Gas Consumption	29
4.2.2.5	Statistical analysis of energy audit data	29
4.3	Results and Discussion	30
4.3.1	Energy Survey Results.....	30
4.3.2	Barn Monitoring Results.....	33
4.3.2.1	Barn A monitoring.....	33
4.3.2.1.1	Description of Barn A.....	33
4.3.2.1.2	Summer Measurement in Barn A	34
4.3.2.1.3	Winter Measurement in Barn A.....	39
4.3.2.2	Barn B monitoring	44
4.3.2.2.1	Description of Barn B.....	44
4.3.2.2.2	Summer Measurement in Barn B.....	45
4.3.2.2.3	Winter Measurement in Barn B	50
4.3.2.3	Barn C monitoring	55
4.3.2.3.1	Description of Barn C	55
4.3.2.3.2	Summer Measurement in Barn C.....	56
4.3.2.3.3	Winter Measurement in Barn C	59
4.3.2.4	Barn D monitoring.....	63
4.3.2.4.1	Description of Barn D.....	63
4.3.2.4.2	Summer Measurement in Barn D	64
4.3.2.4.3	Winter Measurement in Barn D.....	66
4.3.2.5	Correlation between fan energy consumption and indoor air quality	68
4.4	Summary.....	70
5	EVALUATION OF ENERGY CONSERVATION MEASURES USING SIMULATION..	73
5.1	Introduction.....	73
5.2	Methodology.....	74
5.2.1	Model development	74
5.2.2	Heat balance for the control volume approach	76
5.2.3	Total heat generated by the pigs	77

5.2.4	Heat generated by the lights.....	78
5.2.5	Heat generated by the feed motors.....	79
5.2.6	Heat transmission through the building components.....	80
5.2.6.1	Heat loss through the external walls	80
5.2.6.2	Heat loss through the ceiling.....	84
5.2.6.3	Perimeter heat loss through the floor	84
5.2.7	Heat loss through ventilation fans.....	85
5.2.8	Calculation of electrical energy consumption of equipment	85
5.2.8.1	Lights, heat lamps, heat pads, motor and recirculation fans	85
5.2.8.2	Exhaust fans	86
5.2.9	Calculation of gas consumption of space heater in the room monitored	87
5.2.10	Application of simulation model on swine barn	89
5.2.10.1	Room simulation and validation	89
5.2.10.2	Simulation of the annual energy consumption: baseline case	90
5.2.10.3	Application of energy-conservation strategies to the baseline case.....	90
5.3	Results and Discussion	91
5.3.1	Model Validation	91
5.3.1.1	Model Validation for Barn A.....	91
5.3.1.2	Model Validation for Barn B	97
5.3.1.3	Model Validation for Barn C	102
5.3.1.4	Model Validation for Barn D.....	105
5.3.1.5	Verification of electrical energy consumption using ventilation graph and actual inside air temperature on model validation	106
5.3.2	Evaluation of Energy Conservation Strategies to Baseline Case.....	108
5.3.2.1	Lighting.....	108
5.3.2.2	Creep Heating	112
5.3.2.3	Recirculation Fan.....	114
5.3.2.4	Exhaust Fan.....	114
5.3.2.5	Feed Motor.....	117
5.3.2.6	Heat Recovery.....	119
5.3.2.7	Propane-gas fired radiant heater	123

5.4 Summary	124
6 CONCLUSION AND RECOMMENDATION.....	126
6.1 Conclusion	126
6.2 Recommendations.....	128
REFERENCES	129
Appendix A: Survey Questionnaire.....	135
Appendix B: Selection of Barns to be Monitored.....	138
Appendix C: Instruments used in Energy Audit.....	142
Appendix D: Statistical Analysis.....	147
Appendix E: Sol-air Temperature Computation.....	149
Appendix F: Weather Data	156
Appendix G: Sample Calculations on Simulation	159
Appendix H: Computation of Energy Consumed using Graph and Actual Temperature	183
Appendix I: Various Lighting Options used in Building Simulation.....	186
Appendix J: Sensitivity Analysis on Heat Exchanger	187

LIST OF TABLES

Table 3.1	Breakdown of energy use in swine housing	6
Table 3.2	Relative life and efficiencies of various light sources	8
Table 3.3	Optimum inside air temperature and ranges for swine	9
Table 3.4	Typical ventilation rates for pigs	10
Table 3.5	Yearly ventilation energy consumption per animal space in barn.....	11
Table 3.6	Electricity use in swine farms in Ontario.....	14
Table 4.1	List of instruments for barn monitoring.....	26
Table 4.2	Energy cost per animal produced from surveyed barns (2004 – 2006).....	31
Table 4.3	Descriptive statistics for energy cost per animal produced from different barns	32
Table 4.4	Equipment inventory in the rooms monitored for Barn A.....	34
Table 4.5	Descriptive statistics for the parameters measured (Barn A-summer)	36
Table 4.6	Estimated daily total electrical energy consumption (Barn A-summer).....	37
Table 4.7	Daily average electrical energy consumption of equipment in Barn A-summer.....	38
Table 4.8	Descriptive statistics for the parameters measured (Barn A-winter).....	40
Table 4.9	Estimated daily total electrical energy consumption (Barn A-winter)	41
Table 4.10	Daily average electrical energy consumption of equipment in Barn A-winter	42
Table 4.11	Natural gas consumption for different production stages (Barn A-winter)	43
Table 4.12	Equipment inventory in Barn B	44
Table 4.13	Descriptive statistics for the parameters measured (Barn B-summer)	46
Table 4.14	Estimated daily total electrical energy consumption (Barn B-summer).....	47
Table 4.15	Daily average electrical energy consumption of equipment in Barn B-summer	48
Table 4.16	Descriptive statistics for the parameters measured (Barn B-winter)	51
Table 4.17	Estimated daily total electrical energy consumption (Barn B-winter)	52
Table 4.18	Daily average electrical energy consumption of equipment in Barn B-winter.....	53
Table 4.19	Natural gas consumption for different production stages (Barn B-winter)	54
Table 4.20	Equipment inventory in Barn C	56
Table 4.21	Descriptive statistics for the parameters measured (Barn C-summer)	57
Table 4.22	Estimated daily total electrical energy consumption (Barn C-summer).....	58
Table 4.23	Daily average electrical energy consumption of equipment in Barn C-summer	58

Table 4.24	Descriptive statistics for the parameters measured (Barn C-winter)	60
Table 4.25	Estimated daily total electrical energy consumption (Barn C-winter)	61
Table 4.26	Daily average electrical energy consumption of equipment in Barn C-winter.....	61
Table 4.27	Natural gas consumption for different production stages (Barn C-winter)	62
Table 4.28	Equipment inventory in Barn D.....	63
Table 4.29	Descriptive statistics for the parameters measured (Barn D-summer)	65
Table 4.30	Descriptive statistics for the parameters measured (Barn D-winter)	67
Table 4.31	Correlation between fan energy consumption and IAQ (summer and winter).....	68
Table 4.32	Correlation between fan energy consumption and IAQ (all data).....	69
Table 4.33	Average daily electrical energy consumption for four barns in summer.....	70
Table 4.34	Average daily electrical energy consumption for four barns in winter	71
Table 4.35	Accumulated gas consumption for seven days in four barns during winter	71
Table 5.1	Simulated and measured electrical and gas consumption of different equipment....	107
Table 5.2	Annual energy consumption and savings (Barn A: efficient lights).....	110
Table 5.3	Financial analysis on using energy efficient lighting in Barn A.....	111
Table 5.4	Annual energy consumption and savings (Barn A: efficient lamps/pad)	113
Table 5.5	Annual energy consumption and savings (Barn A: efficient recirculation fan)	116
Table 5.6	Annual energy consumption and savings (Barn A: efficient exhaust fan)	116
Table 5.7	Annual energy consumption and savings from (Barn A: efficient feed motor)	118
Table B.1	Selection criteria: type of operation and percent population of swine industry.....	138
Table B.2	Selection criteria: size of operation for farrow-finish and farrow-wean.....	138
Table B.3	Selection criteria: size of operation for grow-finish and nursery.....	139
Table B.4	Selection of two most efficient swine barns	140
Table D.1	Statistical results of two sample t-test.....	148
Table D.2	Interpretation of coefficient of correlation.....	148
Table F.1	A 5-year average weather data in Saskatoon.....	156
Table G.1	Construction materials of building components (Barn A).....	160
Table G.2	Hourly heat generated by pigs in gestation room	166
Table G.3	Fan Specifications.....	168
Table G.4	Calculated UA-value for farrowing room.....	171
Table G.5	Information required in the calculation of heat generated by pigs	171

Table G.6 Heat generated by pigs in the farrowing room.....	172
Table G.7 Heat gain from lights in the farrowing room	173
Table G.8 Heat gain from heat pads in the farrowing room	173
Table G.9 Heat gain from heat lamps in the farrowing room.....	173
Table G.10 Calculated data for determining minimum and maximum ventilation rate	174
Table G.11 Humidity ratio for different outdoor temperature	176
Table G. 12 Ventilation required at different outside temperature using ventilation graph	178
Table H.1 Energy consumption of exhaust fans for 24 hours using ventilation graph.....	184
Table H.2 Energy consumption of exhaust fans for 24 hours using actual inside temperature.	185
Table I.1 Lumen per watt ratings of different lighting options.....	186
Table J.1 Natural gas consumption (Barn A: heat exchanger with different effectiveness).....	187

LIST OF FIGURES

Figure 4.1	Current sensors hooked up to the wire in the electrical panel.....	28
Figure 4.2	Layout of Barn A.....	33
Figure 4.3	Percent distribution of electrical energy consumption (Barn A-summer).....	37
Figure 4.4	Percent contribution of equipment to energy consumption (Barn A-summer).....	38
Figure 4.5	Percent distribution of electrical energy consumption (Barn A-winter).....	41
Figure 4.6	Percent contribution of equipment to energy consumption (Barn A-winter).....	42
Figure 4.7	Percent distribution of natural gas consumption (Barn A-winter).....	43
Figure 4.8	Layout of Barn B.....	44
Figure 4.9	Percent distribution of electrical energy consumption (Barn B-summer).....	47
Figure 4.10	Percent contribution of equipment to energy consumption (Barn B-summer).....	49
Figure 4.11	Percent distribution of electrical energy consumption (Barn B-winter).....	52
Figure 4.12	Percent contribution of equipment to energy consumption (Barn B-winter).....	53
Figure 4.13	Percent distribution of natural gas consumption (Barn B-winter).....	54
Figure 4.14	Layout of Barn C.....	55
Figure 4.15	Percent distribution of electrical energy consumption (Barn C-summer).....	58
Figure 4.16	Percent contribution of equipment to energy consumption (Barn C-summer).....	59
Figure 4.17	Percent distribution of electrical energy consumption (Barn C-winter).....	61
Figure 4.18	Percent contribution of equipment to energy consumption (Barn C- winter).....	62
Figure 4.19	Percent distribution of natural gas consumption (Barn C-winter).....	63
Figure 4.20	Layout of Barn D.....	64
Figure 4.21	Percent contribution of equipment to energy consumption (Barn D-summer).....	66
Figure 4.22	Percent distribution of electrical energy consumption (Barn D-winter).....	68
Figure 5.1	Heat gains and heat losses in a swine production room.....	76
Figure 5.2	Heat transfer through building envelope.....	82
Figure 5.3	Simulated and actual energy consumption in farrowing room (Barn A).....	93
Figure 5.4	Simulated and actual energy consumption in nursery room (Barn A).....	94
Figure 5.5	Simulated and actual electrical energy consumption - grow-finish room (Barn A),	95
Figure 5.6	Simulated and actual energy consumption in gestation room (Barn A).....	96
Figure 5.7	Simulated and actual energy consumption in farrowing room (Barn B).....	98

Figure 5.8	Simulated and actual energy consumption in nursery room (Barn B)	99
Figure 5.9	Simulated and actual energy consumption in grow-finish room (Barn B).....	100
Figure 5.10	Simulated and actual energy consumption in gestation room (Barn B).....	101
Figure 5.11	Simulated and actual energy consumption in farrowing room (Barn C).....	103
Figure 5.12	Simulated and actual energy consumption in gestation room (Barn C).....	104
Figure 5.13	Simulated and actual energy consumption (Barn D:grow-finish room)	105
Figure 5.14	Cross-flow heat exchanger (Source: Del-Air).....	119
Figure 5.15	Heat exchange between exhaust and supply air	120
Figure 5.16	Simulated monthly natural gas consumption (Barn A).....	121
Figure 5.17	Simulated monthly gas consumption (radiant heater).....	123
Figure C.1	Clamp-on transducers (CT), potential transformer (PT) and energy logger.....	Error!
	Bookmark not defined.	
Figure C.2	Split-core current transducers (CTs) and datalogger ...	Error! Bookmark not defined.
Figure C.3	Natural gas and Propane gas meters	Error! Bookmark not defined.
Figure C.4	Temperature and relative humidity sensor.....	Error! Bookmark not defined.
Figure C.5	Ammonia (NH ₃) and hydrogen sulfide (H ₂ S) monitors.....	Error! Bookmark not defined.
	defined.	
Figure C.6	Carbon dioxide (CO ₂) transmitter.....	Error! Bookmark not defined.
Figure E.1	Solar angle for vertical and horizontal surfaces (source: ASHRAE 2005).....	Error!
	Bookmark not defined.	
Figure G.1	Ventilation graph for gestation room.....	Error! Bookmark not defined.
Figure G.2	Ventilation graph for farrowing room	Error! Bookmark not defined.

NOTATION

Symbols:

α	Absorptance of surface for solar radiation
β	Solar altitude, degrees
δ	Solar declination, degrees
Σ	Surface tilt from horizontal, degrees
ϕ	Solar azimuth, degrees
θ	Incident angle, degrees
ε	Effectiveness of heat exchanger, decimal (specified by the manufacturer)
ε_h	Hemispherical emittance of surface
η	Efficiency of the equipment, decimal
ρ_g	Ground reflectivity
ν	Kinematic viscosity, m ² /s
w	Air flow velocity, m/s
x	Characteristic length (i.e. height of the wall or width of ceiling), m
λ_a	Air conductivity, W/(m·K)
ψ	Surface azimuth, degrees
γ	Surface-solar azimuth, degrees
A	Apparent solar constant
A_s	Surface area, m ²
AST	Apparent solar time, decimal hours
B	Atmospheric extinction coefficient
C	Sky diffuse factor found in ASHRAE handbook chapter 31
C_C	Cost of coal used for the month, \$
C_E	Cost of electricity consumed for the month, \$
C_G	Cost of natural gas or propane gas consumed for the month, \$
C_o	Cost of other fuel sources consumed for the month, \$
CN	Clearness number multiplier for clear/dry or hazy/humid locations
CO_2	Carbon dioxide

C_p	Specific heat of air, KJ/kg-K
EC_{ind}	Energy cost per animal marketed for individual barn
EC_{leb}	Energy cost per animal marketed for least efficient barn
EC_{meb}	Energy cost per animal marketed for most efficient barn
E_d	Diffuse irradiance
E_{DN}	Direct normal irradiance
E_F	Energy consumption of the exhaust fans, kWh
E_{gas}	Energy output of the heater, MJ
E_H	Energy consumption of the heaters, kWh
E_{HL}	Energy consumption of the heat lamps, kWh
E_{HP}	Energy consumption of the heat pads, kWh
E_L	Energy consumption of the lights, kWh
E_M	Energy consumption of the feed motors, kWh
E_m	Motor efficiency, as decimal fraction
E_{RFM}	Energy consumption of the recirculation fans, kWh
E_t	Total solar radiation incident on surface, W/m ²
ET	Equation of time, decimal minutes
F	Perimeter heat loss coefficient, W/m
F_h	Fuel consumed by the heater, m ³
F_l	Motor load factor
F_s	Lighting special allowance factor
F_u	Lighting/motor use factor
h	Thermal resistance through convection, W/m ² K
h_i	Heat transfer coefficient by long-wave radiation and convection at inside surface, W/(m ² K)
h_o	Heat transfer coefficient by long-wave radiation and convection at outer surface, W/(m ² K)
H	Hour angle, degrees
H_2S	Hydrogen sulphide
HV_g	Heating value of gas, m ³
I	Current, A

k_n	Thermal conductivity of the construction material n, W/m K
L	Latitude, degrees
LON	Local longitude, decimal degrees of arc
LSM	Local standard time meridian, decimal degrees of arc
LST	Local standard time, decimal hours
\dot{m}	Mass flow rate of the air, kg/s
n	Number of data samples
N_{CS}	Number of culled sows sold for the month
n_e	Number of equipment
N_F	Number of feeders sold for the month
N_G	Number of growers sold for the month
NH_3	Ammonia
Nu	Nusselt number, dimensionless
N_W	Number of weanlings sold for the month
P	Perimeter length of exposed edges, m
P_e	Power rating of the equipment, W
pf	Power factor, decimal
P_m	Motor power rating, W
q_B	Heat transmission through building envelope, W
q_c	Heat transmission through the ceiling, W
q_F	Heat loss through ventilation fans, W
q_f	Perimeter heat loss, W
q_L	Heat gain from lights, W
q_M	Heat gain from feed motor, W
q_{net}	Heating/cooling load, W
q_p	Heat gain from pigs, W
q_w	Heat transmission through the wall, W
ΔR	Difference between long-wave radiation incident on surface from sky and surroundings and radiation emitted by blackbody at outdoor air temperature, W/m ²
R_{ec}	Score based on energy cost

R_i	Thermal resistance of indoor air film, $m^2 K/W$
R_n	Thermal resistance of n layer, $m^2 K/W$
R_o	Thermal resistance of outdoor air film, $m^2 K/W$
R_T	Total thermal resistance to heat flow, $m^2 K/W$
t	Equipment's time of use, h
t_b	Temperature of exhausted air before heat exchanger, $^{\circ}C$
t_e	Sol-air temperature (C or K)
t_i	Indoor air temperature (C or K)
t_o	Outdoor air temperature, K
U	Thermal transmittance or overall heat transfer coefficient, $W/m^2 K$
UC_{ave}	Average monthly energy cost per animal marketed, \$/pig sold
V	Voltage, V
V_a	Actual measured values, kWh or MJ
V_f	Ventilation rate, cfm
V_g	Volume of gas consumed, m^3
V_p	Simulated values, kWh or MJ
W	Total light wattage, W
Δx_n	Thickness of the construction material n, m
Y	Ratio of sky diffuse on vertical to horizontal surface

Acronyms:

CT	Current transformer
$HVAC$	Heating, ventilation and air-conditioning
IAQ	Indoor air quality
MVR	Minimum ventilation rate
PT	Potential transformer
RH	Relative humidity
SD	Standard deviation
TC	Temperature control
THC	Temperature humidity control

1 INTRODUCTION

1.1 Background of the study

Energy input is vital in every operation of swine production as it affects productivity and overall profitability. Some of the challenges that the swine industry is facing include increasing energy cost and decreasing prices of market hogs. Energy prices have risen very rapidly in the last few years. Natural gas has gone from as low as \$0.11/m³ in 1998 to \$0.42/m³ in 2006 and electricity prices have increased from \$0.08/kWh to \$0.11/kWh and further increases are already scheduled (Huffman et al., 2006). According to the National Energy Board (2006), continued upward pressure on price of electricity will be experienced by consumers. The increase in price of electricity was attributed to the increasing cost of developing new generation and transmission facilities. In 2006, approved electricity rate increases for different provinces in Canada ranged from 3% to 15%. On the other hand, hog market prices within Canada have declined by 12% in 2007 (George Morris Center, 2007). Due to losses incurred, numerous swine producers left the industry leading to an 11% decrease of hog inventory in April 2007 (Statistics Canada, 2008). Another issue concerning the use of energy is the problem in greenhouse gases (GHGs) emission which significantly contributes to global warming (Cooper, 2002).

Because swine production entails energy-intensive operations, many research studies were aimed towards improving energy use efficiency to reduce overall production cost and increase the profit margin and market competitiveness of the industry. Most of these studies dealt with benchmarking and simulation. Benchmarking is a process in which different aspects of production operation was assessed and compared to the industry's best practices (Camp, 1989). Various surveys were conducted in different parts of the country to determine the average energy consumption of the industry. The most recent survey conducted showed that in Saskatchewan, the energy expenses in swine production from 1989 to 1997 ranged from 13.4 to 15.4 % of gross operating expenses (Khakbazan, 1999). Barber et al. (1989) estimated the energy cost to be

\$4.00/pig sold for the farrow-finish barns. Because these surveys were conducted several years ago, up-to-date information on the energy cost per animal marketed is needed. In these research surveys conducted, large variability in the energy cost per hog sold was observed. This was attributed to differences in management practices, building construction/insulation, lighting schedules and other areas. Further research should be done to identify the energy use on specific areas of production and quantify the contribution of each area to the total energy consumption in the barn. This can be done through barn monitoring wherein actual measurements of energy use were done.

Other research studies focused on determining impact of different energy conservation measures on energy consumption and production performance. Evaluation of energy conservation measures can be done by in-barn experiment or building simulation. The high cost of conducting in-barn experiments limits the capability of researchers to assess strategies prior to implementation. Building simulation programs suited to livestock applications have not been well established. Three of commercial software packages evaluated for this study (i.e. eQuest, DOE2, and Transys) were designed for simulating residential and office buildings. Thermal comfort, heat production in relation to activities, and occupancy schedule for animals and human were different. Furthermore, most of mechanically ventilated swine barns have exhaust fans that creates the negative pressure inside the building and also serves as the cooling system in the barn. This is not an option in the above-mentioned software packages. Thus, there is a need to develop a model that would simulate the barn using the same fundamental principles of heat transfer and thermodynamics but suited to the conditions in swine barns. Research conducted by Bantle and Barber (1989) used DOE2 to estimate annual energy consumption in poultry barn. Although, good agreement between the predicted and actual energy use was observed in that study, the predicted values can be further improved by considering animal heat production. Other studies were geared towards determination of thermal environment (Barber and Ogilvie, 1980; Li, 2000) which can be used to determine energy consumption. However, only natural gas consumption was measured in these studies. In order to validate the results of the simulation, electrical energy consumption and natural/propane gas consumption should be measured.

Since the swine industry is characterized by volatile prices of inputs, tight margins and stiff competition, a significant reduction in energy costs will help the industry improve its profitability. Hence, this study aimed to determine the current rate of energy consumption and energy use patterns in swine barns, and quantify energy savings that can be realized from implementing various energy-saving strategies. The results of this study were expected to benefit not just the swine producers but also the environment and community. In aiming to create energy efficient barns, this study can also contribute to addressing the problem of excessive emission of GHGs which was reported to have increased by 36% from 1990 to 2004 (Natural Resources Canada Publication, 2006).

1.2 Scope of the study

In order to determine the energy usage in swine barns in Saskatchewan, the survey questionnaire was intended to be widely distributed in the province. There were 336 swine barns in Saskatchewan based on the SaskPork report in 2007. Due to limited resources, at least 10% of the barn population was targeted as survey respondents.

Barn monitoring aimed to measure the actual energy consumption for the entire barn. However, due to limited resources and manpower, only 10% of the surveyed barns were targeted for monitoring and only one room per stage of production within each barn was monitored. The assumption was based on the information that the same type of production room would have the same set-point temperature, pig capacity, equipment, operating schedule, and building construction, thus, the gross energy use in each type of room would be similar on an annual basis.

The simulation part of this study aimed to quantify energy savings associated with implementing different strategies. Since the main goal was to create a baseline case to which energy conservation strategies can be applied and determine the difference in energy consumption, only major components and processes were considered in the calculation of heat transmission through building shell. Research study (Barber, 1991) on ventilation and heating system design showed that the heat transmission through building component have minimal effect on energy

consumption. In a research study on thermal environment simulation (Li, 2000), studs, vapor barrier, and were not considered in the calculation of building heat transmission. Thus, the same assumption was made in this study. It was assumed that when comparing the baseline case and the simulated case of energy-saving strategies applied, the effect of these construction details would be common to both cases, thus, calculating the actual contribution of these components was not necessary. Also, only one room per stage of production was selected for simulation and validation based on the assumption above.

2 OBJECTIVES

The overall goal of the study was to assess current energy use in swine barns and improve energy use efficiency in barns, thereby reducing overall production cost.

This research study specifically aimed to:

- a. conduct a survey to evaluate energy use (\$/animal marketed) in typical swine barns in Saskatchewan;
- b. identify the energy intensive tasks in barns, potential areas for improvement, and best practices on energy management through barn monitoring;
- c. assess the impact of level of energy use on indoor air quality and performance of the operation; and
- d. quantify the impact of different energy-saving strategies on energy cost through building simulation.

3 LITERATURE REVIEW

This chapter covers the uses of energy in swine barns and studies related to energy and environmental parameter monitoring, which served as the basis for the experimental set-up in this study.

3.1 Uses of Energy in Swine Barns

Uses of energy in swine barns include creep heating, water heating, space heating, lighting, ventilation, feed handling, manure handling, and heater/fan controls.

Table 3.1 shows the estimated breakdown of energy consumption for 29 farrow-to-finish barns in Saskatchewan based on the survey conducted by Barber et al. (1989). The results showed that heating and ventilation components are the major contributors to energy use in the different types of swine barns.

Table 3.1 Breakdown of energy use in swine housing

Component	Farrow-Wean barns, %	Grow-Finish barns, %	Farrow-Finish barns, %
1. Heating	65	12	50
2. Ventilation	19	64	32
3. Lighting	13	17	14
4. Materials Handling (i.e. feed, water & manure)	3	7	4

Source: Barber et al. (1989)

From the energy used in heating for farrow-wean barns, approximately 78% was contributed by heat lamps used in creep heating.

3.1.1 Creep heating

In a typical farrowing barn, a temperature range of 18 to 21°C is maintained to provide thermal comfort to sows. However, newborn piglets require more heat which can be achieved by providing creep heater in farrowing barns to provide warm temperature of 32 to 35°C. The most common type of creep heater is the 250-W electric lamp or electric infrared heaters which consume large amount of energy, provide uneven temperature distribution and pose as potential fire hazard (MacDonald et al., 2000; MacDonald 2002). Heat pads have become widely used due to their effectiveness in providing direct heat with minimal wasted energy. However, a study conducted by Zhang et al. (2004) on effectiveness of heat mats versus heat lamps showed that heat lamps were preferred by the piglets during the 1st to 2nd day. In that study, the heat mat has uncontrolled temperature which can go higher than what the piglets required, thus, they rejected it.

3.1.2 Space heating

Gas-fired heaters and hot water heating (HWH) system can all be used in swine barns to provide supplemental heating. Gas-fired heaters have an efficiency of 80% while those that use wood or coal has an efficiency of 70% (MacDonald, 2002). The most commonly used space heating system is a fan-forced unit heater which uses propane or natural gas because of cost considerations and relative efficiency.

Hot water heating (HWH) system consists of a boiler, circulating pump, expansion tank, distributing pipes, radiators in the heated space and various valves, gauges and regulators. Heat distribution was done by forced-air fans, finned tube convectors or black steel pipe. Black pipe is most commonly used in livestock because of the ease in cleaning, less susceptibility to dust, and not easily damaged (Hydro One Network, 2006).

3.1.3 Lighting

Different stages of production require different levels of illumination and photoperiods. The recommended photoperiod is a minimum of eight (8) hours of light per day (CARC, 1993). For breeding/gestation barns, the recommended lighting duration is from 14 to 16 hours to extend the sow's estrus cycle (Clarke et al., 2006). The recommended light intensities of 108 to 161 lumen/m² for breeding and farrowing, 54 lumen/m² for gestation, and 54 to 108 lumen/m² for grower/finisher (Canada Plan Service, 2006).

The commonly used type of lights are incandescent and compact fluorescent but the T-8 fluorescent tubes with electronic ballast mounted in a weatherproof fiberglass with gasket diffuser is more efficient and it lasts longer than incandescent bulb. T-8 lamps are not widely used due to relatively higher cost of T-8 lamps compared to T12 lamps. In high ceiling barns, high intensity discharge (HID) lamps such as metal halide and high pressure sodium systems offer additional energy savings over fluorescent along with lower maintenance cost (MacDonald et al., 2002; PSCI 2001; PSCI 2004). Table 3.2 shows the relative life and efficiencies of various light sources.

Table 3.2 Relative life and efficiencies of various light sources

Lamp Type	Power Rating (W)	Efficiency (Lumens/W)	Typical Lamp Life (hr)
1. Incandescent	25 – 200	11 – 20	750 – 5,000
2. Halogen	50 – 150	18 – 25	2,000 – 3,000
3. Fluorescent T8	32 – 120	88	20,000
4. Fluorescent T5	28 – 100	104	20,000
5. Fluorescent T5 High Output	54 +	93	20,000
6. Compact Fluorescent	5 – 50	50 – 80	10,000
7. Metal Halide	70 – 400	60 – 94	7,500 – 10,000
8. High Pressure Sodium	35 – 400	63 – 125	15,000 – 24,000
9. Light emitting diode (LED)	1.4	47 – 53	100,000

Source: Huffman and MacDonald (2006)

Lighting plays a significant role in reproductive and overall swine production performance. The cost of electricity for lighting is 14 to 17% of the total energy cost of production for swine;

however, with an energy-efficient lighting system there is a potential to reduce energy cost while increasing light intensities and improving pig's performance (Clarke et al., 2006).

3.1.4 Ventilation

All livestock confinement buildings require continuous ventilation year round to maintain comfortable and productive environment. The primary goal of a ventilation system is to provide an environment conducive to optimum production while maintaining acceptable air quality levels for workers and animals. The way ventilation systems operate has a major impact on fan energy use and on supplemental heating. Ventilation systems are designed to vary air flows from minimum ventilation rates in the winter to maximum ventilation rates in the summer. Ventilation rates vary because there are required air exchange at different outside air temperatures. The ventilation system must limit temperature rise during hot weather, control temperature and humidity, and control odours and gases (Fehr, 1992). The barn can be ventilated naturally, mechanically or a combination thereof. The factors which affect the selection of the ventilation system in an agricultural building include intended use of the building (i.e. swine or poultry barn), climatic environment in which the barn is located, building insulation, building layout, and available equipment.

A properly designed and operated livestock ventilation system provides an environment which is desirable for the animals as well as people. Pork Industry Handbook (2000) presented optimum temperatures and allowable ranges for pigs of different age and weight as shown in Table 3.3.

Table 3.3 Optimum inside air temperature and ranges for swine

Animal Age/Weight	Optimum Temperature, °C (°F)	Desirable Limits of Temperature, °C (°F)
1. Lactating Sow	16 (60)	10 – 21 (50 – 70)
2. Litter, newborn	35 (95)	32 – 38 (90 – 100)
3. Litter, 3 weeks old	27 (80)	24 – 29 (75 – 85)
4. Pre-nursery, 5 – 14 kg (12 – 30 lb)	27 (80)	24 – 29 (75 – 85)
5. Nursery, 14 – 23 kg (30 – 50 lb)	24 (75)	21 – 27 (70 – 80)
6. Nursery, 23 – 34 kg (50 – 75 lb)	18 (65)	16 – 21 (60 – 70)
7. Growing-Finishing	16 (60)	10 – 21 (50 – 70)
8. Gestating Sows	16 (60)	10 – 21 (50 – 70)
9. Boars	16 (60)	10 – 21 (50 – 70)

Source: Pork Industry Handbook (2000)

Table 3.4 shows the minimum ventilation required for pigs with mechanical ventilation system installed (Pork Industry Handbook, 2000). This information can serve as a guide in selecting proper fan sizes. A paper by Huffman et al. (2006) discussed the importance of maintaining both the desired environmental temperature for the pigs being housed as well as exchanging sufficient air to maintain good air quality for maximum pig performance.

Table 3.4 Typical ventilation rates for pigs

Animal age/weight	Minimum winter ventilation, l/s/head (ft ³ /min/head)	Maximum summer ventilation, l/s/head (ft ³ /min/head)
1. 5 kg	0.7 (1.5)	8.5 (18)
2. 25 kg	1.4 (3.0)	16.5 (35)
3. 50 kg	1.9 (4.0)	23.6 (50)
4. 75 kg	2.4 (5.0)	30.7 (65)
5. 100 kg	2.8 (6.0)	35.4 (75)
6. 120 kg	3.3 (7.0)	37.8 (80)
7. Gestation/Breeding	4.7 (10.0)	94.4 (200)
8. Farrowing	7.1 (15.0)	141.6 (300)

Source: Pork Industry Handbook (2000) and Huffman et al. (2006)

Another way of reducing energy cost is through the use of heat exchangers to recover heat from the exhaust air. Results of the studies (MacDonald, 1984; MacDonald, 1985; Overhults and Fehr, 1986) on heat recovery in livestock operations showed that the energy cost was sensitive to minimum ventilation rate (MVR) and heat exchanger effectiveness. High MVR and heat exchanger effectiveness resulted to higher energy savings. The results also showed that frost was developed during extreme cold weather conditions, which greatly affected the performance of the heat exchanger. It was recommended to further investigate the method of defrosting the ice accumulated in heat exchangers during winter.

Moreover, a combination of mechanical and natural ventilation can be implemented. Fans can be used in winter and natural ventilation for warm weather periods (MacDonald, 2002). Timmons (1990) did an analysis on a 500-cow dairy facility in Wolcott, New York to determine the effect of using natural ventilation system. The results showed that the use of automatic curtain control can save energy while providing rapid response to quick changing environmental conditions.

OMAFRA (1994) provided an estimate of yearly energy consumption per animal space for both exhaust and internal air circulation systems as shown in Table 3.5.

Table 3.5 Yearly ventilation energy consumption per animal space in barn

Animal Type	Exhaust Fan Energy, kWh	Circulation Fan Energy, kWh
Gestating Sows	59	20 – 30
Farrowing Sows	180	100 – 130
Weaning pigs (7-25 kg)	25	8 – 17
Grow-Finish pigs (>25 kg)	32	6 – 10

Source: OMAFRA (1994)

3.1.5 Feed and manure handling

Lemay (1999) discussed importance on proper feed and manure handling which affects dust and gas concentration and odour emission. Ensuring proper management and maintenance procedures as well as good husbandry practices to maintain optimum environmental conditions in the barn can reduce energy by efficient use of ventilation. Clean pens can reduce the level of NH₃ in the room. During manure removal from the room, H₂S is released and ventilation rate should be increased to levels above the required ventilation rate to reduce H₂S concentration to allowable limit. Dust levels can be reduced in a barn by minimizing feed handling and disturbance and by avoiding disturbance of the pigs (Andries, 2006).

3.2 Indoor Air Quality Measurement (IAQ)

In the implementation of energy-conservation strategy, one of the factors that should be considered is the production performance of the animals. Research studies (Renaudeau et al., 2006; Stowell et. al, 2001) showed that pig's performance was affected by the thermal environment and the level of noxious gases such as carbon dioxide (CO₂), hydrogen sulfide (H₂S) and ammonia (NH₃). To comply with occupational health regulations, workers in swine barns should not be exposed to more than 25 ppm ammonia, 10 ppm hydrogen sulfide and 5,000 ppm carbon dioxide over the course of their workday (OSHA, 1989). Maintaining the gaseous and particulate contaminants below the allowable level is the major consideration in maintaining good indoor air quality (McQuiston et al., 1994). Nienaber et al. (1991) conducted a study on the

effect of thermal environment on feeding patterns and swine performance. The results showed that at high temperature ranging from 33°C to 35°C, the feed intake, and growth rate of 40-100 kg pigs were reduced by 13-26% and 20-28%, respectively.

Many of studies (Riskowski et. al. 1988; Neinaber 1988; Donham 1990; Ricalde et.al. 2000) have correlated indoor environmental parameters to pig performance. The results obtained in these studies showed that there is a negative effect of extremely low or high temperatures on feed intake and consequently on their weight gain and fat gain from farrowing to weaning. Although gas concentration and dust levels inside the barn can also affect the pig performance, no correlation was made between gas concentration and pig performance. Further research is needed to investigate the relationship between energy input and indoor air quality through actual barn monitoring.

A protocol for determination of environmental parameters in animal housing was developed by Wheeler et al., (2001). Certain factors should be considered in measuring environmental parameters in swine barns. Location of temperature and relative humidity sensors should be at the animal-occupied zone. Sensors need to be protected to prevent pigs from destroying them and to prevent excessive exposure to contaminants such as manure, dust from feeds, and other materials that may affect the sensor performance. Recent development in sensor technology has made data gathering easy and inexpensive. New sensors have compact design and equipped with internal datalogging system which make it less cumbersome for data gathering and analysis while ensuring accuracy and reliability of information. The recommended data collection period was one week and the data interval is 15 – 30 minutes. This was deemed to be adequate data collection period to capture the activity in the barn.

Sun (2005) and Wang (2007) monitored diurnal and seasonal odour and gas emission profiles in a farrow-finish swine barn using thermocouples and RH sensor connected to datalogger (CR 1000, Campbell Scientific, Edmonton, Alberta, Canada). Gas concentrations were measured using three different analyzers. Diurnal pattern was observed for CO₂, NH₃ and H₂S concentration and a linear regression model was developed. Among the past studies geared towards measuring environmental parameters, none has correlated the level of energy used to gas

concentrations. Ventilation is a major contributor to energy use in the barn as shown in a previous survey conducted by Barber (1989). Because the level of gas concentrations is affected by the ventilation system inside a room, correlating these two parameters can establish a relationship that can be considered in the implementation of energy saving strategies. This is important in assessing the effectiveness of the strategy on reducing energy cost while maintaining good indoor air quality.

3.3 Studies on Energy Consumption in Swine Barns

In 1988, Ford and Barber conducted a survey of 29 farrow-to-finish swine barns located in Saskatchewan with size ranging from 35 to 360-sow operation. They have estimated the energy cost per animal marketed to be \$4.00/hog marketed. They also observed that the average energy consumption of swine barns in Saskatchewan was 1,200 kWh/sow or 80 kWh/hog marketed, which was based from the three-year energy costs and production data. However, they observed a large variability in energy use among barns (700 to 1,800 kWh/sow). They attributed this to the different management practices, building construction and insulation, lighting schedules, and use of heat recovery system. Due to this variability experienced in in-barn experiments, it is difficult to show the impact of the different energy saving strategies on energy costs (Barber et al., 1989). Although, they have identified the sources of variation, the study was not able to quantify the contribution of each variation to energy use. The procedure used in other surveys conducted (Boris, 1986; Driggers, 1976) in different provinces like Manitoba and Ontario were similar as cited by Ford and Barber's studies.

A comparative study of energy use in 14 hog barns in Saskatchewan and Manitoba was conducted by Khakbazan (1999). The time-series data gathered from different barns were analyzed and used to rank the 14 barns according to energy use per hog. The most efficient barn was found to be using propane as fuel source which is more efficient than other sources of fuel. It was also observed in that study that the same large variability in the gathered energy data were associated with the management practices, size and type of operation and other environmental variables. This study also showed that monthly averages of 76,920 kWh of electricity and 14,053 m³ of gas were consumed in the surveyed barns during 1996-1999.

Another electricity benchmarking study was conducted on Ontario swine barns. The audit was conducted on 2 farrowing, 10 farrow-to-finish, 2 farrow-to-nursery, 3 finishing, 1 nursery-to-finish, and 3 nursery barns. Electricity bills and production data were collected from each barn and the energy utilization index was computed and summarized in Table 3.6.

Table 3.6 Electricity use in swine farms in Ontario

Swine	Farrow kWh/sow	Farrow- Finish kWh/100 kg	Farrow- Nursery kWh/100 kg	Finish kWh/100 kg	Nursery kWh/100 kg	Nursery- Finish kWh/100 kg
kWh (Max)	338	44	136	17	19	16
kWh (Ave)	296	31	91	12	14	16
kWh (Min)	254	11	46	9	12	16

Source: OMAFRA (2006)

However, the conditions in Saskatchewan are not similar to the conditions in Ontario. Factors such as temperature, relative humidity, solar intensity, wind velocity and other weather parameters can affect the energy use in different locations. Thus, results of study done in Ontario may not be comparable to energy use in Saskatchewan but are useful information in evaluating the variability of energy use in farms across Canada.

A study on actual measurement of energy consumption was done in Manitoba (Harder, 2008). In this study, they have developed BarnMax, which is a visual management tool for resources consumption. In this system, actual and optimum consumption values for electricity, fuel, feed and water in hog farms were measured and calculated in real-time, thus served as an alarm if the actual values are not within the optimum values. The optimum value was obtained using historical energy data. In 2003, 15 hog finisher barns in Manitoba were investigated. Results showed that the annual energy consumption range from 75 MJ/pig to 300 MJ/pig while the annual energy cost range from \$0.90/pig to \$3.50/pig. The high variability observed was associated with the level of process management and lack of visual monitoring of energy consumption. In this study, they developed a proto-type system that would log the alternating current and transform the data into energy consumption. This system used sensors and dataloggers to monitor consumption in real-time. The problems encountered in the implementation of this system are the remote accessibility of farms and capital cost.

3.4 Studies on Energy Conservation Strategies in Swine Barns

Various conservation strategies on creep heating, heating, and ventilation system have been explored by many researchers. Research conducted by Zhang et al. (2004) compared the effect of heat pads and electric lamp on pig's performance. There was no significant difference observed in terms of pig's mortality rate and mass gain. Another study was conducted by Boris (2008), which compared the pig's performance and cost effectiveness of using heat pads and heat lamps. Two farrowing rooms with 44 crates in a 3,100-sow farrow-isowean barn were selected. Double-size heat pads (22 units at 130 W or 65 W per crate) were placed in one room and 44 infrared heat lamps (175 W) was placed on the other room. The results showed that there was no significant difference in the weight gain and mortality rate between heat lamp and pad rooms. The heat lamps used typically consumed 1279 kWh per crate per annum while heat mats consumed 383 kWh per crate per annum. Despite the research studies conducted on heat lamps and heat pads, the management of creep heating system varies from barn to barn. Thus, a model that would predict the consumption of heat lamps or heat pads or combination of the two should be developed.

Lambert, et al (2001) conducted a research which involved modeling of three humidity control strategies and its effect on energy consumption. The computer simulation was done to compare three strategies based on energy requirement and air quality. The results showed that the Temperature-Humidity-Control (THC) strategy with 75% RH set-point and 5% proportional band was the optimum strategy compared to the Temperature Control (TC) strategy. The THC strategy provided very good control on temperature and relative humidity which dictates the operations of the fans, which can reduce energy consumption. Although, results showed relatively useful information on energy requirement for each control strategy, most barns employed temperature control strategy. Temperature control system is just one of the many areas (i.e. lighting, ventilating, heating, and management) where conservation measures can be applied. A research study that will compare the conservation measures in different areas previously mentioned is needed to give the swine producers more options in selecting and implementing appropriate energy conservation strategies.

Barber and Ford (1989) conducted a field evaluation of an air-to-air heat exchanger in a swine weanling room. The result showed that the heat recovery of the specific model of heat exchanger used ranged from 0.08 kW/°C to 0.10 kW/°C. This indicates that the higher the heat recovery, the higher reductions in energy consumption can be attained. Although there is no existing measure of the average heat recovery, it was considered that this result can help in reducing energy consumption. The results of the evaluation was barn specific, thus, there is a need to develop a general model of assessing the energy savings that would be applicable to most type of barns. Furthermore, there was no benefit-cost analysis done on this research. The same research was conducted by Meyer (1983). In that study, fifteen (15) heat exchangers of five (5) different brands were monitored to determine heat recovery performance when installed in typical swine barns in Ames, Iowa. The results showed that the heat transfer rate for the 15 units ranged from 0.8 t 1.21 kJ/(h-m³/s-°C) and an average of 1.12 kJ/(h-m³/s-°C). Also, the effectiveness ranged from 0.48 to 0.67 and an average of 0.56. The results implied that different effectiveness or percent heat recovery varies from different type and size of heat exchangers, therefore, a heat exchanger with high effectiveness and high heat transfer rate should be chosen.

Another study conducted by MacDonald (1984) analyzed an air-to-air heat exchanger in weaner room using the Better-Air B-400 model. The results showed that for the 138 day test period, the estimated energy savings on electrical heat was 6,625 kWh. The abovementioned studies done on heat exchangers were mostly barn specific and greatly depended on the performance of the different models of heat exchanger. A model that would predict the energy savings for most types of barn and different models of heat exchanger should be developed.

Other energy conservation strategies in areas such as building layout and insulation, altering minimum ventilation, fan selection, thermostat setting, and use of heat exchangers and solar energy were discussed by Fehr (1992). The paper enumerated different strategies but no actual experiment was conducted and has not mentioned if assessment was made on these conservation measures.

3.5 Studies on Building Simulation

Building simulation is a powerful and cost-effective tool in determining the effect of energy conservation strategies on energy saving costs. Software packages like eQuest, DOE2 and Transys are based on the principles of thermodynamics and heat transfer; however, these programs are suited for commercial and residential buildings. Bantle and Barber (1989) used DOE 2.1C in simulating the annual energy consumption of a poultry barn. The results showed a 16.4% difference between the simulated and actual electrical energy use in summer and 19.8 % difference in winter. On the other hand, the difference between the predicted and measured value on natural gas consumption was found to be 9.3%. It was concluded that there was a good agreement between the predicted and measured energy consumption. Swine barns are far more complex than the description of the simulated poultry barn. The poultry barns have supply fans while swine barns have exhaust fans with different ventilation stages. Thus, DOE 2.1C or the higher version would not be suited for this application because of the different type of ventilation system and operation. It was also recommended that further improvement can be made by considering the details on occupant loads of animals rather than just the building structure and operating procedure.

Research studies were done to simulate the thermal environment of swine barn and relate it to energy consumption. Barber and Ogilvie (1980) conducted research on predicting the indoor temperature in swine barn. The program developed was only used to simulate the thermal environment in swine building and the effectiveness of different control strategies. This led to the development of an improved model through the research conducted by Li (2000). The research was done to simulate the thermal environment of grow-finish barn and included the solar air temperature. A user-friendly simulation program using visual basic was also developed. The simulation program could be used in analyzing the effect of construction materials on the thermal response, the performance of various controllers and equipment, and energy consumption of a housing system. Comparison between the simulated and actual energy consumption was done on natural gas only. Stalvent, which is a software developed in Denmark, also works on the same principle of heat transfer and thermodynamics but focused only on ventilation and heating systems and applied the CIGR 2002 equation on animal heat production (Pedersen et al., 2005;

Morsing et al., 2005). In this study, not only ventilation and heating system was considered but also other equipment (i.e. feed motor, light, heat pad, heat lamp and recirculation fan) in the barn.

Morsing et al., (2005) conducted a study on simulating grow-finishing houses in Portugal, Finland and Denmark. The study compared the results of the simulated energy consumption among the swine barns in three different locations but there was no actual measurement of energy consumption done for the barns. The results of the study showed that energy consumption increases with increasing outside temperature which is expected. The results showed that the energy consumption for heating the barn is highly dependent on temperature set-point but no explanation as to why they obtained such results. This study also observed differences between dry and wet conditions of the barn. Higher energy consumption was observed in wet conditions than in dry, because additional energy was required to remove additional moisture inside the barn. Thus, total heat production of animals is pertinent in computing for the energy requirement to maintain a comfortable environment for pigs and workers. Heinonen (2005) conducted a study in which simulation of hog barn and development of a simpler equation to calculate energy consumption for ventilation system were done. There was no validation done between the simulated and actual consumption. In this study, the equation was used on calculating energy consumption for equipment, which was validated with the actual measured value.

Animal heat production is a vital part of building of simulation. Studies done by some researchers aimed to model the animal heat production. Pedersen et al. (2005) simulated heat requirement and air quality in weaner houses. Albright (1990) referenced the American Society of Agricultural Engineers standard (ASAE) D270.4 on animal heat and moisture production. However, numerous studies (Brandl et al., 2004; Christianson et al., 2002; Pedersen, 2002; Pedersen et al., 2002) have developed a correction on the ASAE standards. In the standard, the weight of the pigs and outside temperature that pigs were exposed to were the only parameters included. In recent studies, the level of animal activity was accounted for and an equation developed for correcting animal heat production.

3.6 Research Studies Needed

Based from literature review, benchmark information on energy use in swine barns are needed to improve energy efficiency in their operations. However, the most recent energy survey in Saskatchewan was done nine years ago. Other surveys were conducted in Ontario and Alberta. Weather conditions in different provinces within Canada are variable which affects the level of energy use in a building. Therefore, there is a need to obtain up-to-date information on energy consumption in typical swine barns in Saskatchewan. Updated information is necessary to adapt to the changes on prices of energy, feeds, and hogs marketed. Barn monitoring has been done in other provinces and their results only showed the electricity use for the entire barn. Thus, it is aimed in this research to determine the contribution of each production stage (i.e. farrowing, nursery, gestation and grow-finish stages) and each piece of equipment (i.e. creep heater, space heater, feed motor, lights, and fans) to the total energy consumption in order to identify areas for improvement and to prioritize conservation strategies to apply. Furthermore, more research studies concentrated on measuring environmental parameters but have not correlated any of these parameters to the level of energy use in the barn. It is important to determine the correlation to assess the strategy's effectiveness on reducing energy consumption while maintaining good indoor air quality for pigs and workers. Therefore, this research aimed to determine the correlation between the noxious gases concentration and fan energy consumption.

Building simulation is an inexpensive way of modeling a system. By changing variables in a mathematical model, predictions of the behavior of the system can be made. Most of the simulation done in agricultural building aimed at determining the thermal environment. Only one study compared the 48-hr simulated and actual values of indoor air temperature and accumulated natural gas consumption in grow-finish rooms. However, electrical energy consumption was not measured and simulated. Computer simulation software packages (i.e. eQuest, DOE, Transys, etc) are commercially available but the model are based on residential and other commercial buildings. Thus, this study aimed to develop and evaluate mathematical model that can be used to simulate the electrical and natural/propane gas consumption in different production stages in swine barn. It also aimed to evaluate different energy conservation strategies without going

through in-barn experiments, thus, providing a cost-effective way of assessing plans for energy management.

4 DETERMINATION OF ENERGY USE THROUGH BENCHMARKING

4.1 Introduction

Benchmarking is a process in which organizations assess different aspects of their production operation in relation to the industry's best practices (Camp, 1989). The goal of this phase of the study is to gather information on existing management practices and up-to-date information on energy consumption in typical swine barns in Saskatchewan.

Benchmark information can be determined by conducting a survey and actual barn monitoring. Studies on energy consumption in swine barns (Khakbazan, 1999; Ford and Barber, 1988) were done several years ago and needed to be updated as market conditions continually changes. Recent survey in other province (OMAFRA, 2006) was conducted but weather conditions and pricing structure between provinces varies. Thus, survey was conducted in this study to determine the most recent energy use trends among barns in Saskatchewan. To be able to determine the sources of variations on energy use, actual barn monitoring should be conducted. Actual barn monitoring was conducted in other provinces (i.e. Manitoba and Alberta) which have different weather conditions from Saskatchewan.

Up-to-date information is important in assessing the efficiency of operations within the same type of barn. Actual monitoring of energy use would also be useful in determining the areas that contribute the most to energy consumption. Energy-saving strategy can be applied to these areas to attain significant cost reduction. Thus, survey, barn monitoring and energy audit were conducted in this study.

4.2 Materials and Methods

4.2.1 Energy survey

4.2.1.1 Development of the survey questionnaire

Consultations with different experts in the swine industry were done to develop the questionnaire. The draft questionnaire was sent to five leading producers for pre-screening prior to wide distribution. The survey questionnaire was modified based on the pre-screening response and the final version is shown in Appendix A.

The survey was conducted on different types of barn or production stages (i.e. farrowing, nursery, grow-finish, and gestation). Gestation period is the interval from conception to farrowing. Gestation period ranged from 113-116 days or 3 months, 3 weeks and 3 days. Farrowing is the act of giving birth to piglets and then sows are weaned every 2nd or 3rd week. Weaning is the process of removing the pigs from the sow and moving them to nursery room. Pigs stayed in nursery room for 6-10 weeks of age and then transferred to grow-finish room. Marketing of pigs from grow-finish room normally occurs after 12 weeks at an average weight of 115-120 kg. A farrow-finish barn would cover the four stages of production while others barns were designed specifically for gestation, farrowing, nursery, or grow-finish only, or a combination of two production stages (i.e. gestation-farrowing).

The information requested in the survey are the physical location of the barn, type of operation, size of operation, average body weight of pigs going in and out of each production stage, three-year production data on hogs marketed per month and three-year energy (i.e. electricity and gas) costs per month. These minimum information were required to determine the energy costs per pig marketed (\$/pig sold) and to enable the grouping of respondent barns according to type of operation. The energy utilization index (EUI) expressed in terms of \$/pig sold was used for comparing barns because this is the industry accepted index.

4.2.1.2 Sampling method and distribution of questionnaire

Due to time factor and availability of potential respondents, convenient sampling was done to select the respondents from Prairie Swine Center Inc. (PSCI) database of swine producers. In this sampling method, the barns were selected based on the accessibility and availability of respondents (Quinn and Keough, 2002). A total of 26 swine producers were contacted and have requested to participate in the survey.

4.2.1.3 Analysis of the survey results

The information gathered from the survey conducted were analyzed by computing for the average monthly energy cost per pig sold (\$/pig sold) as shown in equation 4.1.

$$EUI_{ave} = \frac{C_E + C_G + C_C + C_o}{N_W + N_F + N_G + N_{CS}} \quad (4.1)$$

where:

EUI_{ave} is the average monthly energy cost per pig sold, \$/pig sold

C_E is the cost of electricity consumed for the month, \$

C_G is the cost of natural gas or propane gas consumed for the month, \$

C_C is the cost of coal used for the month, \$

C_o is the cost of other fuel source for the month, \$

N_W is the number of weanlings sold for the month

N_F is the number of feeders sold for the month

N_G is the number of growers sold for the month

N_{CS} is the number of culled sows sold for the month

The energy cost per animal marketed was computed to compare the energy usage among barns. To determine the central tendency and variability of data obtained in the survey, descriptive

statistics was used to analyze the data. Using two-sample comparison (proc t-test using SAS v.9.1), comparison of energy consumption per animal marketed between barns was done.

The 3-yr average energy cost per pig sold was also used as one of the criteria for selecting the barns in which energy audit were conducted. The other two criteria used for rating the participating barns were type of operation (i.e. farrow-to-finish, grow-finish, farrow-to-wean, etc) and size of operation (i.e. number of sows, feeders or weanlings). The ratings were based on the highest frequency distribution and given a 5-point score. The criteria and ratings to select the most and least energy efficient barns are shown in Appendix B.

4.2.2 Barn Monitoring

Barn monitoring included conducting an inventory of equipment, building inspection, and energy audit. A systematic way of identifying the energy use profile in a building is through conducting energy audit. Through actual measurement of building energy use, potential energy savings can be identified. The energy audit is an inspection and analysis of energy flow in the barn with the objective of understanding the energy usage profile (Thumann and Younger, 2005). Audit was conducted to seek opportunities to reduce the amount of energy usage without negatively affecting the animal's production performance. By determining the area that consumed the most energy, the greater the opportunity to significantly reduce the total energy cost.

In order to determine the amount of energy consumed for the entire year, actual measurement of electrical and natural gas consumed by equipment for one room in each production stage was done during winter and summer seasons. Energy consumption for most operations in the barn (e.g. lights, feed motor, etc.) is relatively constant throughout the year; however, variations may occur during summer when all fans are in full operation and during winter when all heaters are running and only few fans are running.

Electrical energy, gas consumption, and indoor air quality parameters such as indoor air temperature and relative humidity, and gas concentrations of ammonia (NH₃), hydrogen sulphide (H₂S) and carbon dioxide (CO₂) were measured for at least seven (7) consecutive days in

selected production rooms. Monitoring of barns was done during peak hottest or coldest months to represent the seasonal measurement for summer (July – September 2007) and winter (December – March 2008). One room from each production area (i.e. farrowing, nursery, gestation, and grow-finish) was randomly selected in each barn. Devices with sensors and dataloggers for different parameters were installed in the selected rooms. Barn-specific biosecurity procedure was strictly observed. Research personnel can not enter a barn within two (2) days after being in another barn. Also, no materials or instruments can be transferred between barns, thus, four sets of new instruments were acquired (one for each barn) to prevent possible transfer of diseases from one barn to another.

4.2.2.1 Instrumentation

The list of instruments used for conducting energy audit is shown in Table 4.1. Illustrations, detailed description of the mechanism and calibration of the sensors are shown in Appendix C. Most of the sensors and dataloggers were configured to record data at an interval of 10 minutes for at least seven (7) consecutive days for each selected room in each barn.

Table 4.1 List of instruments for barn monitoring

Parameters to be measured	Instrument	Accuracy and other features
1. Temperature and Relative Humidity	Hobo U12-012	Datalogger with internal sensors for measuring temperature (thermistor), relative humidity (capacitance) and external channel for 4-20mA sensor Range: - 20°C to +70 °C; 5% to 95% RH Accuracy: $\pm 0.35^\circ\text{C}$ Temp; $\pm 2.5\%$ RH
2. Gas Concentrations		
a. Carbon Dioxide (CO ₂)	Vaisala CO ₂ Transmitter (Non-Dispersive Infrared sensor)	Range: 0 – 5,000 ppm Accuracy: $\pm (2\%$ of range + 2% of reading) Output: 4-20mA that can be connected to Hobo U12
b. Ammonia (NH ₃)	Draeger PAC 7000 (electrochemical sensor)	Range: 0 – 300 ppm Accuracy: $\pm 3\%$ of measured value With internal datalogging capability
c. Hydrogen Sulphide (H ₂ S)	Draeger PAC 7000 (electrochemical sensor)	Range: 0 – 100 ppm Accuracy: $\pm 5\%$ of measured value With internal datalogging capability
3. kWh measurement		
a. Datalogger for Voltage and Current Sensors	Hobo Energy Logger	Memory: 512K With 3 flexmart modules that can accept a total of 6 sensors (1 voltage and 5 current sensors)
b. Voltage	T-Mag-SPT-15	150 Volt Potential Transformer Accuracy: $\pm 1\%$
c. Current	T-Mag-SCT-50 T-Mag-SCT-100 T-Mag-SCT-200	0-50 Amp, 0-100 Amp and 0-200 Amp split-core AC current transformers Accuracy: $\pm 1\%$
	CTV-A Onset CTV-B Onset	0-25 Amp and 0-50 Amp split core AC current transformers Accuracy: $\pm 4\%$
4. Natural Gas meter	AC-250 & AL-425	Diaphragm type meter Accuracy: ± 1 unit (x 100 ft ³) Minimum reading is 1 unit.

4.2.2.2 Measurement of Electrical Energy Consumption

Alternating current (AC) transducers and voltage potential transformers attached to a datalogger (Onset Computer Corporation, Bourne, MA) were used to monitor electrical energy consumption for the selected room. These current sensors were hooked up to the wires in the electrical control panel (i.e. circuit breakers for lights, fans, heaters and motors) to measure the contribution of the individual equipment to the total kWh use in the room monitored. The split-core AC current transformers (CTs) shown in Figure 4.1 were mounted by clamping around the current carrying wire, thus, facilitating the installation without the need to shut down the electricity. This was an important consideration so as not to disrupt the operation inside the barn. The capacity of the CTs depended on the current drawn by the equipment on each circuit. The number of CTs installed varied from room to room and from barn to barn. This depended on the number of circuits allocated for the various equipment (i.e. fans, lights, motors, and heaters) in the room.

For lights, fans, heat lamps, and heat pads, datalogging was set to record the data every 10 minutes to get an hourly average of 6 data points for each measured current and voltage. For feed motors, the datalogger was set to log every 1 minute to get an hourly average of 60 data points. This was done to capture the total time that the motor was operated, which was usually less than 10 minutes. Electrical energy consumption was computed using equation 4.2.

$$E = V I \text{ pf } t \quad (4.2)$$

where:

E is the electrical energy consumed of the equipment (i.e. feed motors, light, fans), kWh

V is the measured voltage, V

I is the measured current, A

pf is the power factor of the equipment (specified in equipment)

t is the equipment's time of use (recorded by the datalogger), h

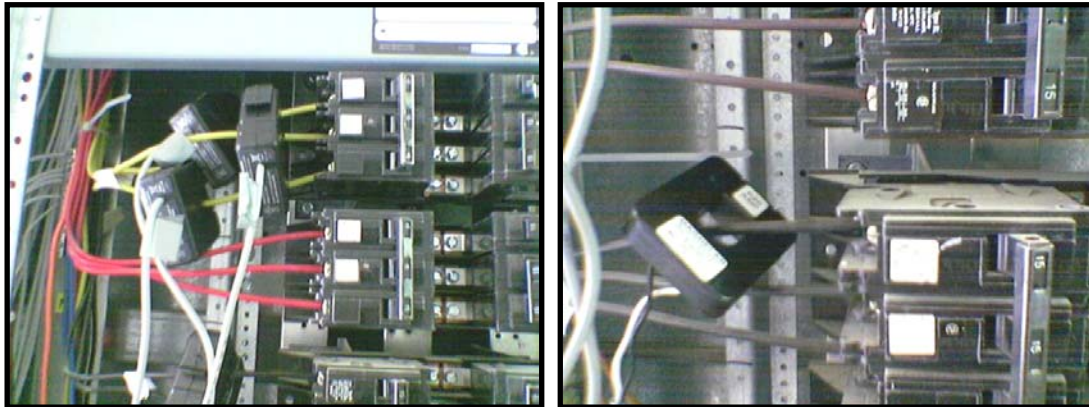


Figure 4.1 Current sensors hooked up to the wire in the electrical panel

4.2.2.3 Measurement of Indoor Air Quality Parameters

The devices listed in Table 4.1 equipped with sensors and data logging capability were used to monitor temperature and relative humidity and gas concentrations of NH_3 , H_2S and CO_2 . An existing barn temperature sensor (thermist) controls the operation of the fans and heaters and was located at the center of the room about 1.5 m above the ground. This was the basis for choosing the same location for temperature and humidity sensors (Onset Computer Corporation, Bourne, MA) used in this study. The devices equipped with electrochemical sensors (Draeger Safety Inc., Pittsburgh, PA) used for measuring NH_3 and H_2S concentrations were located near the exhaust fans at about the same height. The CO_2 transmitter (Vaisala Inc., San Jose, CA) was installed along with other gas sensors and connected to the Hobo U12 datalogger. All gas sensors were of diffusion type, thus, the sensors were installed near the exhaust fan (Wang, 2000) because the general air flow was towards that direction. Data logging interval was set to 10 minutes to get an hourly average of 6 data points. Dataloggers and sensors were set to collect data for at least 7 consecutive days.

4.2.2.4 Measurement of Natural/Propane Gas Consumption

Natural/propane gas consumed (m^3) for each production room was measured through sub-metering. Gas meters (AC-250 and AL-425, IMAC Systems, Pennsylvania, USA) were installed in the same selected production rooms to determine the gas consumption. The readings from the gas meters installed for each heater in the selected rooms were manually recorded on day 1 and day 7 to obtain the accumulated gas consumption (m^3) for one week. The energy output of the heater was computed based on the volume of gas consumed and its heating value as shown in equation 4.3.

$$E_{gas} = V_g \cdot \eta \cdot HV_g \quad (4.3)$$

where:

E_{gas} is the energy output of the heater, MJ

V_g is the volume of gas consumed, m^3

HV_g is the heating value of gas, m^3 (35 MJ/ m^3 for natural gas and 94 MJ/ m^3 for propane gas)

η is the heater's efficiency as per equipment specification, decimal

4.2.2.5 Statistical analysis of energy audit data

Descriptive statistics was used to analyze the measured energy consumption from the four selected barns. Additionally, the fan energy consumption in the rooms monitored was correlated with the actual measured indoor air parameters using simple linear correlation (SAS v.9.1 proc corr).

4.3 Results and Discussion

4.3.1 Energy Survey Results

The energy survey was conducted from December 2006 to February 2007. From the three-year information (2004-2006) on energy consumption and hog production numbers obtained from 28 swine barns, energy cost per pig sold (\$/pig sold) for each barn were computed. Table 4.2 shows the data for the individual barns and Table 4.3 shows descriptive statistics done on the collected data. It was observed that there was a wide range of variability in energy use between types of barns and even within the same type of barns.

Information gathered from Barns 1 and 10 were discarded as these were barns where research activities contribute the most to energy consumption and do not operate in the same capacity as commercial barns. In statistical analysis, the two barns were considered outliers and were not included in the computation.

Using t-test for two samples, comparisons were made between the different types of barns. The result of the statistical test is shown in Appendix D. The average energy cost between types of barns were significantly different ($P < 0.05$) for all comparisons except between grow-finish and farrow-wean barns ($P > 0.05$). These differences were expected because farrow-to-finish operation consumed most energy on a per head basis, while barns that specialized in a single stage operation such as grow-finish, nursery and farrow-wean consumed less energy. This difference was attributed to the energy required for various operations in different stages of production from farrowing, gestation, nursery, and grow-finish.

Table 4.2 Energy cost per animal produced from surveyed barns over three years (2004 – 2006)

Barn No.	Type of operation	Energy cost, \$/year	Average produced pigs per year	Energy cost per pig sold	
				\$/pig sold	\$/100-kg pig sold
1		\$80,151	7,372	\$10.87	\$11.86
2		\$75,657	7,012	\$10.79	\$8.86
3		\$90,626	7,619	\$11.89	\$10.22
4	Farrow-to-finish barns (Including Feedmill cost)	\$125,564	26,002	\$4.83	\$6.10
5		\$60,324	8,951	\$6.74	\$5.76
6		\$127,019	19,806	\$6.41	\$5.19
7		\$65,703	25,532	\$2.57	\$3.99
8		\$46,241	10,857	\$4.26	\$3.56
9		\$94,926	22,272	\$4.26	\$3.54
10		\$98,764	7,584	\$13.02	\$11.52
11		\$108,079	13,335	\$8.10	\$7.17
12	Farrow-to-finish barns (Excluding Feedmill cost)	\$54,098	6,666	\$8.12	\$6.58
13		\$179,489	23,760	\$7.55	\$6.40
14		\$97,625	25,796	\$3.78	\$6.00
15		\$190,328	30,928	\$6.15	\$5.28
16		\$38,751	7,840	\$4.94	\$4.27
17	Nursery	\$96,273	142,340	\$0.68	\$2.24
18		\$69,551	138,691	\$0.50	\$1.66
19		\$45,343	26,339	\$1.72	\$2.59
20		\$45,831	21,475	\$2.13	\$1.89
21	Grow-to-Finish	\$66,887	38,925	\$1.72	\$1.51
22		\$43,757	28,672	\$1.53	\$1.34
23		\$40,858	30,461	\$1.34	\$1.17
24		\$4,237	9,706	\$0.44	\$0.38
25			\$59,623	34,866	\$1.71
26	Farrow-to-wean	\$61,205	14,273	\$4.29	\$14.30
27		\$129,819	166,846	\$0.78	\$8.52
28		\$128,975	151,548	\$0.85	\$8.24

Note: Size of operation for farrow-to-finish and farrow-to wean was based on the number of sows while that for nursery and grow-finish were based on number of feeders and weanlings.

Table 4.3 Descriptive statistics for energy cost per animal produced from the different types of barns

Type of barn	Size range	No. of barns, n	Energy cost per animal produced			
			\$/head pig sold		\$/100-kg pig sold	
			Range	Average (SD)	Range	Average (SD)
Farrow-Finish	300 to 1,500 sow	9	3.0 -12.0	6.8 (3.41)	3.5-12.0	6.56 (3.05)
Farrow-Finish (excluding feedmill)	300 to 2,000 sow	7	3.8-13.0	6.5 (2.98)	6.0-11.5	6.75 (2.31)
Grow-Finish	10,000 to 40,000 feeders/weanlings	6	1.3-2.1	1.7 (0.58)	1.2-2.6	1.7 (0.74)
Nursery	130,000 to 140,000 feeders/weanlings	2	0.5-0.7	0.6 (0.12)	1.7-2.2	2.0 (0.41)
Farrow-wean	150 to 1,200 sow	4	0.8-4.3	1.9 (1.64)	8.2-17.8	12.2 (4.67)

The computed standard deviation reflects the wide range of individual barn’s energy usage within the same type of barn which can be attributed to the different fuel sources used (i.e. natural gas, propane and coal), equipment used and management practices employed in the barn. This indicated that there are significant opportunities for improving energy use practices in some barns in order to reduce overall energy costs.

Thorough investigation was needed to identify the specific tasks that caused the observed variability. The barns which used the most energy per pig and those which used the least energy were selected. Based on the ratings, 5 of the most and 5 of the least efficient barns were selected as shown in Appendix B. Consent to conduct detailed monitoring of energy and air quality in the barn was sought from the owners/managers of these barns until a set of four barns agreed; two of the barns were among those which used the most energy per pig and the other two were among those which used the least energy per pig.

4.3.2 Barn Monitoring Results

4.3.2.1 Barn A monitoring

4.3.2.1.1 Description of Barn A

Barn A was selected because it was one of the least efficient from the 28 surveyed barns. It is a 600-sow farrow-to-finish barn and has an average of 13,000 hogs marketed per year weighing an average of 113 kg each. The barn has a T-type layout as shown in Figure 4.2. There were 8 farrowing rooms with 16 farrowing crates each, 8 nursery rooms with 320 pigs per room, 1 stall gestation room with 300 sows, 1 group gestation room with 300 sows and 14 grow-finish rooms with 400 pigs per room. Table 4.4 shows the equipment inventory in one monitored room for each stage of production.

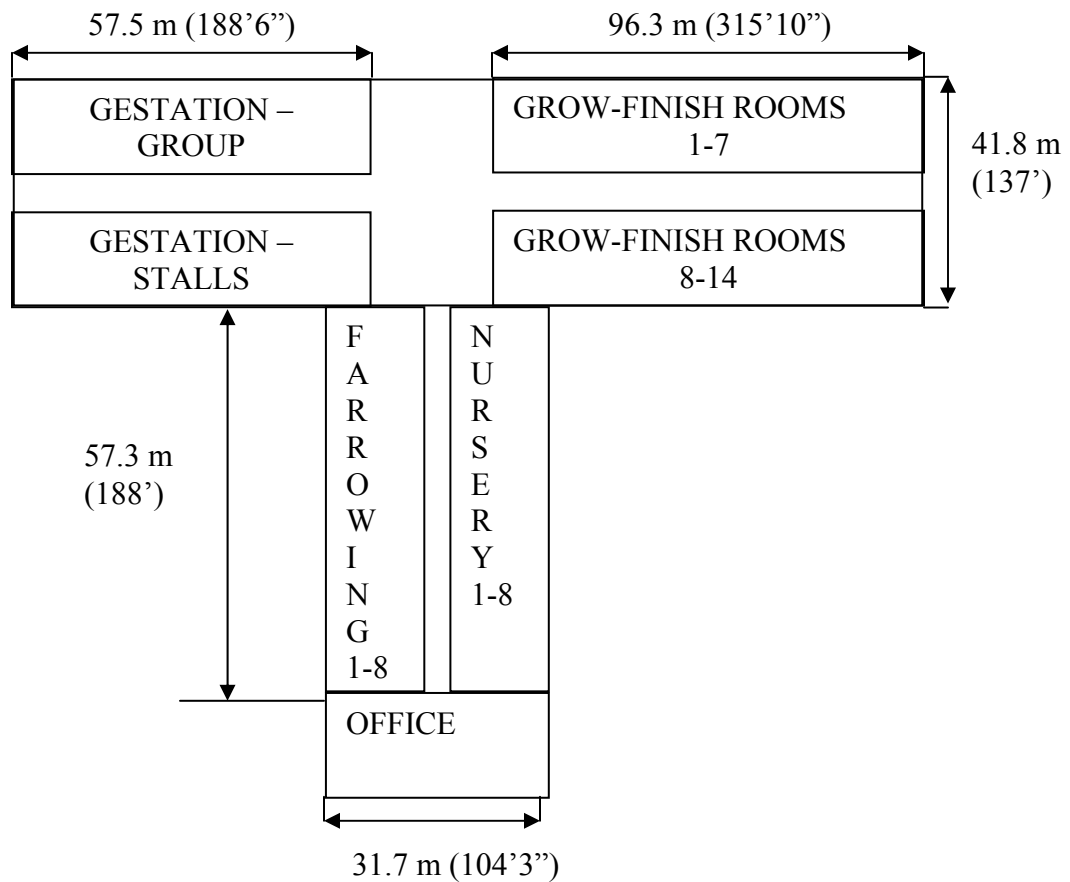


Figure 4.2 Layout of Barn A

Table 4.4 Equipment inventory in the rooms monitored for Barn A

Equipment	Gestation Room	Farrowing Room	Nursery Room	Grow-Finish Room
1. Fluorescent lamp (T12) with 2 lamps per fixture	96 tubes	20 tubes	20 tubes	22 tubes
2. Feed motor	5 (0.5 hp)	-	1 (0.5 hp)	3 (0.5 hp)
3. Exhaust fans	2 (1936 cfm), 3 (6704 cfm) and 3 (12653 cfm)	2 (1936 cfm and 4935 cfm)	1 (2758 cfm) and 2 (4935 cfm)	3 (4935 cfm) and 2 (6704 cfm)
4. Recirculation fans	3 (3368 cfm)	2 (600 cfm)	2 (600 cfm)	1 (3368 cfm)
5. Space heater	3 (80,000 BTU)	1 (80,000 BTU)	1 (225,000 BTU)	1 (225,000 BTU)
6. Heat lamps (175 W)	-	16	-	-
7. Heat pads (169W)	-	8	-	-

4.3.2.1.2 Summer Measurement in Barn A

The summer measurement for nursery, farrowing, gestation, and grow-finish rooms in barn A was conducted from July 16th – 23rd; July 23rd - 30th; July 30th to August 5th; and August 5th-13th, 2007, respectively. Table 4.5 shows the daily average, minimum and maximum values of parameters measured for all types of rooms.

During the monitoring period in each room, the concentrations of H₂S, NH₃ and CO₂ in nursery room was observed to be the highest. This can be attributed to the activities of the pigs and the higher temperature set-point of 28°C in this room. In gestation and farrowing rooms, movement of sows was restrained by the stalls, thus, a lower concentration was observed due to this minimal movement. On the other hand, in grow-finish rooms and nursery rooms, pigs were relatively active and free to move as they were grouped in 20 pigs per pen. Because of the relatively high activity of small pigs in nursery rooms, a higher gas concentration was observed specifically CO₂ because frequent movement of animals entailed higher respiration rate. The set-point temperature for gestation, farrowing, nursery and grow-finish rooms were 20°C, 24°C, 28°C, and 21°C, respectively. The electrical energy consumption per day in the farrowing, nursery, grow-finish and gestation rooms was 3.75 kWh/pig (1.63 kWh/100-kg pig), 0.08 kWh/pig (0.33 kWh/100-kg pig), 0.17 kWh/pig (0.25 kWh/100-kg pig) and 0.40 kWh/pig (0.16 kWh/100-kg pig), respectively as shown in Table 4.5.

Table 4.6 and Figure 4.3 show that the grow-finish area had the highest contribution (50%) to the estimated total electrical energy consumption for the entire barn, followed by farrowing at 25%, gestation at 14% and nursery at 11%. The grow-finish area consumed the most in terms of electrical energy which can be explained by its relative proportion of the total production area of the barn compared to the other stages (i.e. 50% grow-finish; 30% gestation; 11% farrowing; and 11% nursery area). It can also be attributed to the lower temperature set-point in the grow-finish room of about 19°C to prevent heat stress on the pigs. All stages of fans were running to maintain this lower set-point and provide comfortable environment to the pigs, thus, resulting to higher electrical consumption for fan operation. In farrowing rooms, the major energy consuming equipment were heat lamps, heat pads and the stage 1 and 2 fans. In gestation and nursery rooms, all stages of fans were running and these were the major contributors to electrical energy consumption in these rooms.

Table 4.5 Descriptive statistics for the parameters measured (Barn A-summer)

Parameters	Gestation				Farrowing				Nursery				Grow-Finish			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Outside temp, °C	19	3	16	23	23	3	19	26	23	1	22	24	17	3	13	22
Room temp, °C	22	2	20	24	25	2	23	27	28	1	28	29	23	2	20	26
Set-point temperature, °C	20				24				28				21			
RH, %	64	5	59	68	59	7	52	71	63	3	58	66	61	7	54	71
H ₂ S, ppm	2	2	0	5	0	0	0	0	1	0	1	1	0	0	0	1
NH ₃ , ppm	0	0	0	1	0	0	0	0	12	2	10	14	1	2	0	5
CO ₂ , ppm	765	137	627	901	689	54	667	799	1,104	78	1,005	1,195	912	101	744	1,026
Heat lamp, kWh/day	-	-	-	-	12	14	0	35	-	-	-	-	-	-	-	-
Heat pad, kWh/day	-	-	-	-	13	5	9	21	-	-	-	-	-	-	-	-
Stage 1&2 fans, kWh/day	40	7	37	51	28	2	26	30	15	0.4	15	16	39	0.4	39	40
Stage 3&4 fan, kWh/day	74	20	42	87	-	-	-	-	3	1	2	4	22	8	7	33
Recirculation fan, kWh/day	-	-	-	-	2	0.003	2	2	2	0.2	1	2	-	-	-	-
Lights, kWh/day	21	12	4	35	4	0.005	4	4	5	1	4	6	8	0.04	8	8
Feed motor, kWh/day	2	1	1	3	-	-	-	-	1	0.1	1	1	0.2	0.3	0	1
TOTAL, kWh/day	136	19	106	155	60	17	41	79	26	2	23	28	69	8	55	80
n for computing means (# of days)	5				6				6				7			
Pig Inventory				336				16				320				400
Average mass, kg				250				230				25				70
Total pig mass (kg)				84,000				3,680				8,000				28,000

Note: The min, max, means, and standard deviation for all parameters measured were computed on a daily average. Average daily energy consumption was calculated by adding the 10-minute energy consumption in one day.

Table 4.6 Estimated daily total electrical energy consumption (Barn A-summer)

	Gestation	Farrowing	Nursery	Grow-Finish	Barn Total
Electrical energy, kWh/room*	136	60	26	69	
No. of rooms	2	8	8	14	
Room Total	272	479	209	967	1,927

*kWh is computed based on the daily average values.

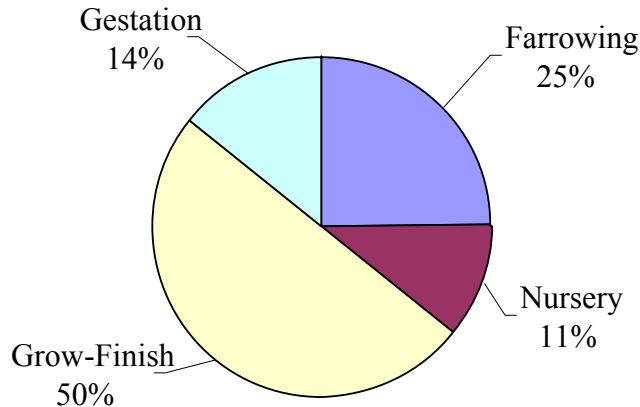


Figure 4.3 Percent distribution of electrical energy consumption (Barn A-summer)

A break down of the contribution of specific equipment using energy in the various rooms showed that fan operations for the four rooms monitored had the highest electrical energy consumption during summer (Table 4.7 and Figure 4.4). This was attributed to the high ventilation rate for each room to remove the heat gain inside the room and maintain the temperature at its set-point. It was also observed that the stage 1&2 fan electrical energy consumption was higher than the stage 3&4 fans. This was expected because stage 1&2 fan was a variable fan which was running continuously while stage 3&4 fans were on/off fans that operated only when additional ventilation was required to remove heat. Another major contributor to energy use in farrowing room was the heat lamps and heat pads (20-22%) and lights (7.3%). For other rooms, lights contributed 11-20% of total energy use. Applying energy conservation strategies on these areas could mean significant reduction in energy use.

Table 4.7 Daily average electrical energy consumption of various equipment in different production stages (Barn A-summer)

Equipment	Gestation	Farrowing	Nursery	Grow-Finish
Heat lamp, kWh/day	0	12	0	0
Heat pad, kWh/day	0	13	0	0
Stage 1&2 fans, kWh/day	40	28	15	39
Stage 3&4 fan, kWh/day	74	0	3	22
Recirculation fan, kWh/day	0	2	2	0
Lights, kWh/day	21	4	5	8
Feed motor, kWh/day	2	0	1	0
TOTAL, kWh/day	136	60	26	69

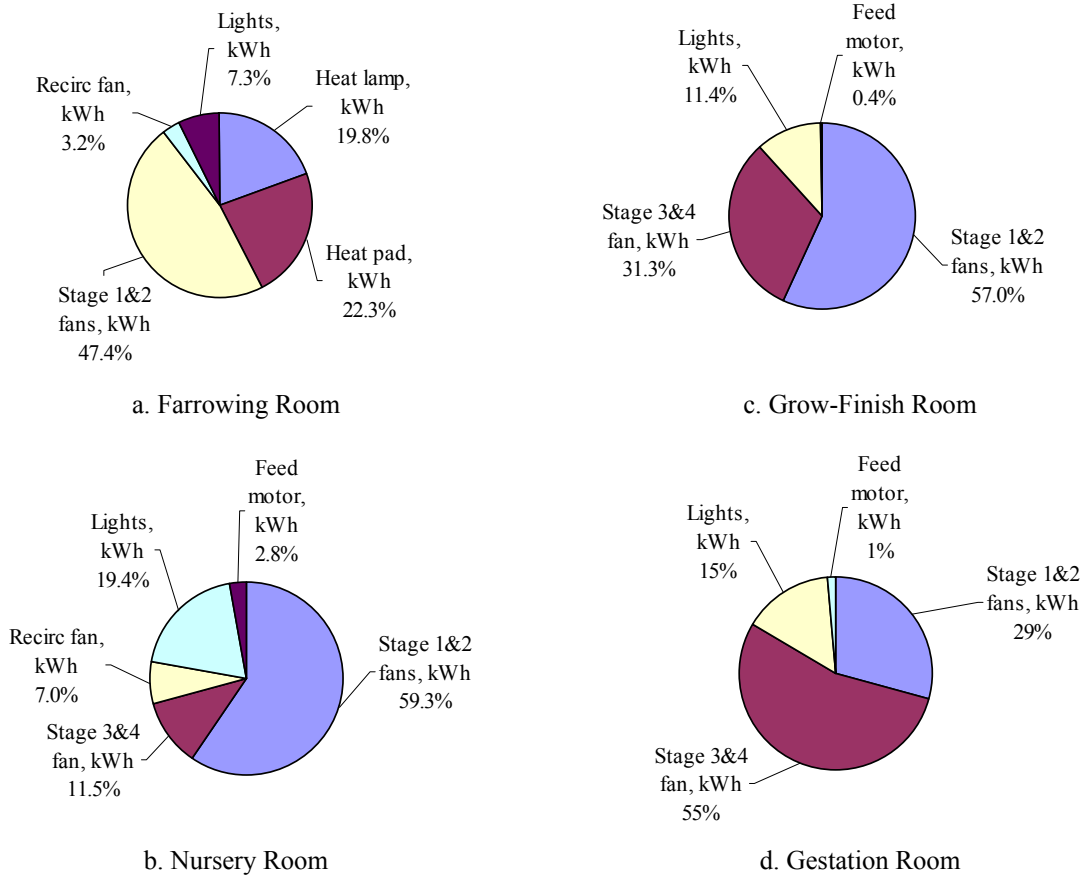


Figure 4.4 Percent contribution of various equipment to the daily average electrical energy consumption in different stages of production (Barn A-summer)

4.3.2.1.3 Winter Measurement in Barn A

Winter measurement for gestation, nursery, farrowing and grow-finish rooms in barn A was conducted in December 21st – 27th (2007), December 27th (2007) to January 3rd (2008), January 3rd – 10th (2008) and January 21st – 28th (2008), respectively. Table 4.8 shows the daily average, minimum and maximum values of parameters measured for all types of rooms.

During the winter measurement for all rooms monitored, it was observed that the concentration of H₂S, NH₃ and CO₂ were relatively higher than that measured during summer. Lower ventilation rate was set during winter to prevent cold draft but adequate to keep gas levels below allowable limit. The higher gas concentrations in winter can be attributed to this reduced ventilation rate. Ventilation rate is the rate of air exchange from outside and inside of the building. This is a measure of how much stale barn air was exhausted and replaced by fresh air from the outside. The electrical energy consumption per day in the farrowing, nursery, grow-finish and gestation rooms was 4.64 kWh/pig (\$2.02 kWh/100-kg pig), 0.16 kWh/pig (0.63 kWh/100-kg pig), 0.09 kWh/pig (0.13 kWh/100-kg pig) and 0.28 kWh/pig (0.11 kWh/100-kg pig), respectively.

Table 4.9 and Figure 4.5 show that the farrowing area (8 rooms) had the highest contribution (35%) to total electrical energy consumption followed by grow-finish at 28%, nursery at 27% and gestation at 10%. Despite the relative size of grow-finish area, farrowing area consumed the most energy during winter. This was due to reduced ventilation rate resulting to decrease in electrical energy consumption of the fans in both areas. With heat lamps and heat pads still following the same operation in winter (similar to summer), farrowing room contributed the most to total energy consumption.

Table 4.8 Descriptive statistics for the parameters measured (Barn A-winter)

Parameters	Gestation				Farrowing				Nursery				Grow-Finish			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Outside temp, °C	-12	8	-22	-5	-8	7	-16	1	-14	5	-20	-8	-16	5	-24	-11
Room temp, °C	18	0	18	19	19	1	18	21	25	1	24	26	19	1	18	19
Set-point temperature, °C	18				19				25				19			
RH, %	76	3	73	81	66	2	65	69	58	4	54	64	87	2	84	91
H2S, ppm	1	0	1	1	1	0	1	2	2	0	2	3	2	0	2	3
NH3, ppm	2	2	0	5	3	3	0	8	10	3	6	13	7	1	6	7
CO2, ppm	2,802	523	2,348	3,422	1,852	593	1,255	2,785	3,037	281	2,721	3,529	3,679	346	3,100	4,201
Heat lamp, kWh/day	-	-	-	-	27	25	0	50	-	-	-	-	-	-	-	-
Heat pad, kWh/day	-	-	-	-	18	0.1	18	18	-	-	-	-	-	-	-	-
Stage 1&2 fans, kWh/day	17	2	15	19	5	0.1	5	5	13	2	11	16	17	1	14	18
Stage 3&4 fan, kWh/day	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-
Recirculation fan, kWh/day	24	0.1	23	24	7	0.02	7	7	2	0.01	2	2	-	-	-	-
Lights, kWh/day	30	0.1	29	30	5	0.01	5	5	14	0.04	14	14	11	0.03	11	11
Feed motor, kWh/day	1	0.04	1	1	-		-	-	0.31	0.04	0.25	0.34	2	0.2	1	2
Heater, kWh/day	0.3	0.4	0.1	1.0	4	0.2	3	4	21	9	12	33	0	0	0	0
TOTAL, kWh/day	72	1	70	73	65	25	38	88	50	8	43	61	30	2	27	32
n for computing means (# of days)	5				6				6				7			
Pig Inventory		260				14				320				320		
Average mass, kg		250				230				25				70		
Total pig mass (kg)		65,000				3,220				8,000				22,400		

Note: The min, max, means and standard deviation for all parameters measured were computed on a daily average. Average daily energy consumption was calculated by adding the 10-minute energy consumption in one day.

Table 4.9 Estimated daily total electrical energy consumption (Barn A-winter)

	Gestation	Farrowing	Nursery	Grow-Finish	Barn Total
Electrical energy, kWh/room*	72	65	50	30	
No. of rooms	2	8	8	14	
Room Total	143	524	402	422	1,490

*kWh is computed based on the daily average values.

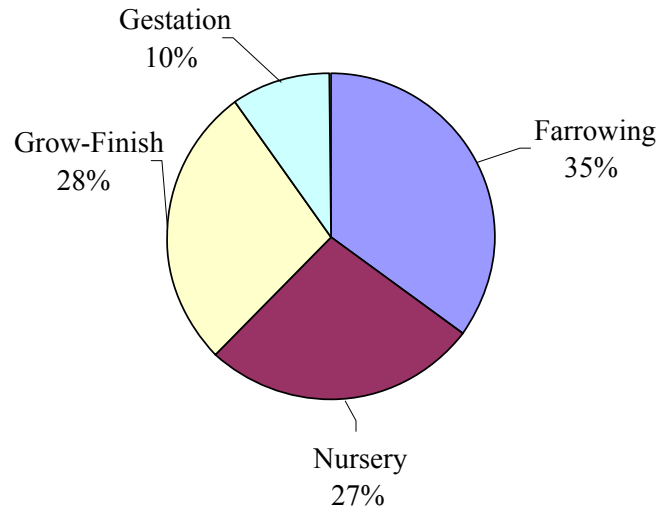


Figure 4.5 Percent distribution of electrical energy consumption (Barn A-winter)

Table 4.10 and Figure 4.6 show that farrowing had the highest electrical energy consumption because of the heat lamp and heat pad. During summer, the grow-finish rooms had the highest consumption because of the high ventilation rate. However, a lower ventilation rate during winter had reduced the fan energy consumption for all rooms. The major contributor to energy use in nursery room was the heater operation (41.2%). This can be explained by the high temperature (28°C) set in this room to provide comfort for the piglets. In the farrowing room, heater blower contributed 5.4% to energy usage. This is relatively small compared to nursery room because the sow's comfort zone was set to 19 °C while the piglets had creep heating (lamps or pads) to provide a warmer environment (maximum of 40 °C). For grow-finish and gestation rooms, the heat generated by the pigs contributed significantly to maintain the room's set-point temperature, thus, required minimal or no supplemental heat from the space heater. Another area where improvement can be made is with lights which contributed 7.1%, 27%, 18.8% and 42% of total energy use in the farrowing, nursery, grow-finish, and gestation rooms, respectively.

Table 4.10 Daily average electrical energy consumption of various equipment in different production stages (Barn A-winter)

Equipment	Gestation	Farrowing	Nursery	Grow-Finish
Heat lamp, kWh/day	-	27	-	-
Heat pad, kWh/day	-	18	-	-
Stage 1&2 fans, kWh/day	17	5	13	17
Stage 3&4 fan, kWh/day	-	-	-	-
Recirculation fan, kWh/day	24	7	2	30
Lights, kWh/day	30	5	14	11
Feed motor, kWh/day	1	-	0.3	2
Heater, kWh/day	0	4	21	0
TOTAL, kWh/day	72	65	50	30

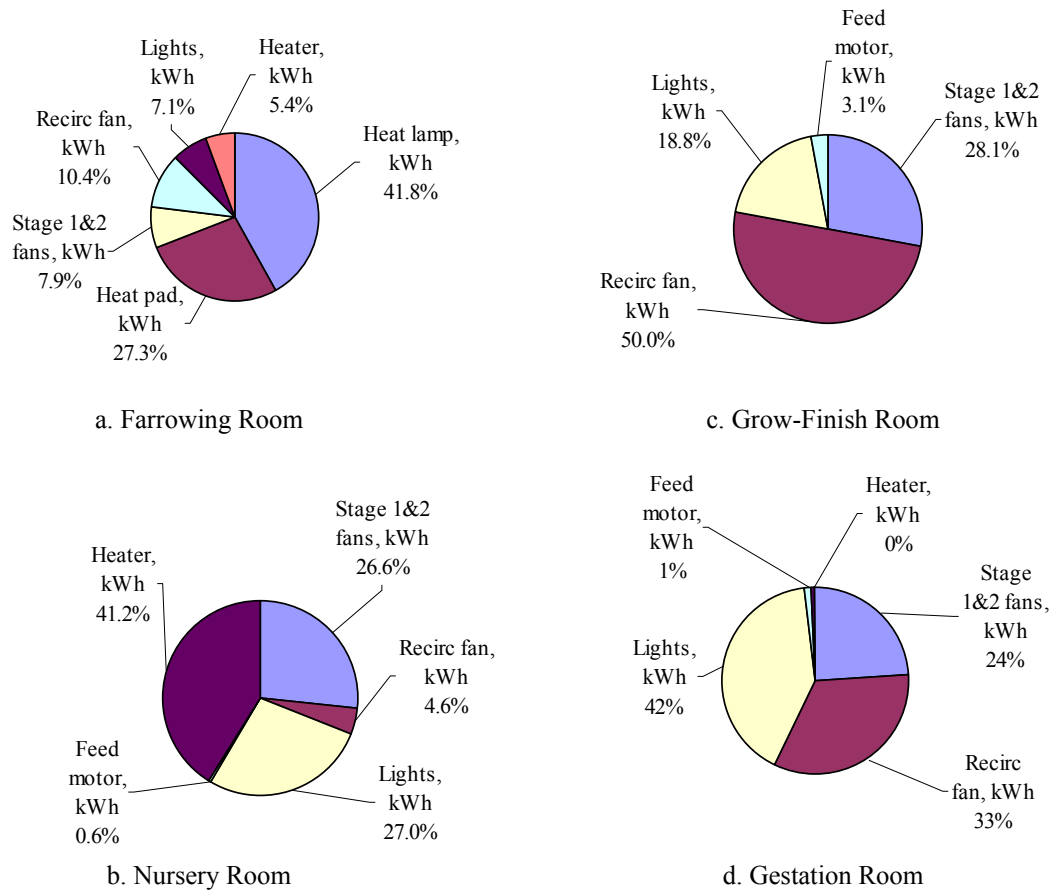


Figure 4.6 Percent contribution of various equipment to the daily average electrical energy consumption for different stages of production (Barn A-winter)

Table 4.11 and Figure 4.7 show the natural gas consumption for barn A measured during winter. Among the four rooms monitored, nursery room had the highest gas consumption. This can be attributed to the high temperature set-point of 26°C to 28°C. The natural gas consumption in gestation room only contributed 6% to the total gas consumed since heat generated by the sows was sufficient to maintain the set-point temperature in the room. The outside temperature during the time of measurement was shown in Table 4.8.

Table 4.11 Natural gas consumption for different production stages (Barn A-winter)

	Accumulated natural gas consumed for 7 days	
	m ³	MJ
Farrowing	57	2,151
Nursery	345	13,121
Grow-Finish	0	0
Gestation	6	217

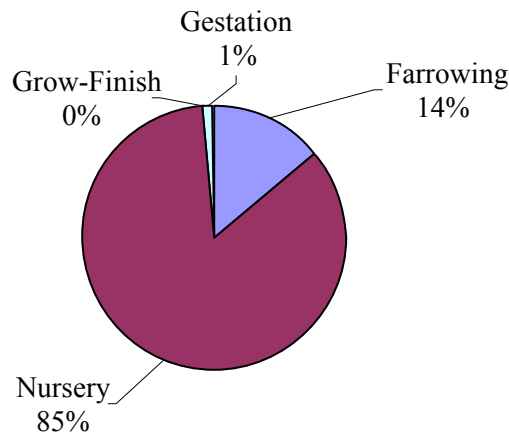


Figure 4.7 Percent distribution of natural gas consumption for different stages of production (Barn A-winter)

4.3.2.2 Barn B monitoring

4.3.2.2.1 Description of Barn B

Barn B was selected because it was one of the most efficient from the 28 surveyed barns. It is a 300-sow farrow-to-finish barn and had an average of 7,500 pigs marketed per year weighing an average of 114 kg each. There were 5 farrowing rooms with 12 crates each, 1 farrowing room with 6 crates, 6 nursery rooms with 133 pigs per room, 1 gestation room with 82 sows, 1 breeding room with 84 stalls and 18 grow-finish rooms with 130 pigs per room. Table 4.12 shows the equipment inventory in each type of room. Barn layout is shown in Figure 4.8.

Table 4.12 Equipment inventory in Barn B

Equipment	Gestation Rooms	Farrowing Rooms	Nursery Rooms	Grow-Finish Rooms
1. Fluorescent lamp (T12) with 2 lamps per fixture	30 tubes	8 tubes	6 tubes	6 tubes
2. Feed motor	2 (2 hp & ½ hp)	1 (2 hp)	1 (2 hp)	1 (1 hp)
3. Exhaust fans	3 (6455 cfm)	1 (6455 cfm)	1 (6455 cfm)	2 (6455 cfm)
4. Heat lamps (175 W)	-	12	-	-
5. Heat pads (120W)	-	12	-	-

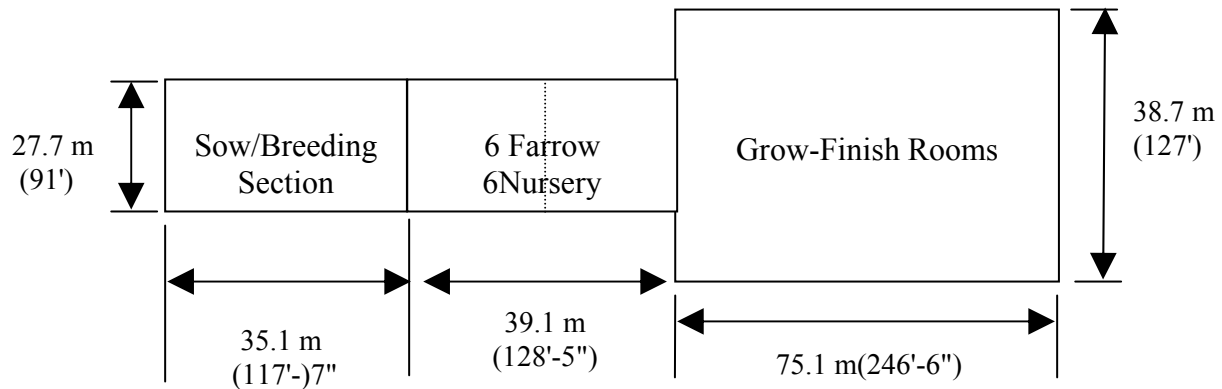


Figure 4.8 Layout of Barn B

4.3.2.2.2 Summer Measurement in Barn B

The summer measurement for farrowing, gestation, nursery and grow-finish rooms in barn B was conducted in September 6th – 14th; September 14th – 21st, September 21st – 27th; and September 27th to October 4th (2007), respectively. Table 4.13 shows the daily average, minimum and maximum values of parameters measured for all types of rooms.

During summer measurement in each room, the concentrations of H₂S, NH₃ and CO₂ in nursery room was observed to be the highest. This was the same observation with that in Barn A. This was due to correlation between gas concentration and level of animal activities in each room, manure management, and set-point temperature. In gestation and farrowing rooms, minimal movement of sows resulted to lower concentration. On the other hand, in grow-finish rooms and nursery rooms, pigs had relatively high level of activities as they can freely move within the pen. Because of this, a higher gas concentration was observed specifically CO₂ because frequent movement of animals entailed higher respiration rate. The set-point temperatures for gestation, farrowing, nursery, and grow-finish rooms were 19 °C, 21 °C, 24 °C, and 19 °C, respectively. The electrical energy consumption per day in the farrowing, nursery, grow-finish and gestation rooms was 2.67 kWh/pig (0.40 kWh/100-kg pig), 0.16 kWh/pig (0.83 kWh/100-kg pig), 0.14 kWh/pig (0.46 kWh/100-kg pig) and 0.24 kWh/pig (0.10 kWh/100-kg pig), respectively.

Table 4.13 Descriptive statistics for the parameters measured (Barn B-summer)

Parameters	Gestation				Farrowing				Nursery				Grow-Finish			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Outside temp, °C	12	5	7	19	10	4	3	15	9	3	4	14	10	3	7	15
Room temp, °C	20	2	18	23	22	1	20	23	24	1	24	25	17	2	15	20
Set-point temperature, °C	19				21				24				19			
RH, %	45	14	26	59	46	2	43	50	61	2	60	64	50	7	43	61
H2S, ppm	0	0	0	0	1	0.1	1	1	1	0.5	1	2	1	0	1	1
NH3, ppm	0	0	0	0	2	1	0	4	4	4	0	9	0	0	0	0
CO2, ppm	1,081	266	703	1,379	1,134	201	863	1,472	2,473	215	2,272	2,815	1,036	113	882	1,182
Heat lamp, kWh/day					0.3	0.0	0.3	0.3								
Heat pad, kWh/day					15	0.1	15	15								
Stage 1&2 fans, kWh/day	13	1	13	15	13	0.4	13	14	20	0.3	19	20	18	4	14	24
Stage 3&4 fan, kWh/day	12	9	2	25												
Stage 5&6, kWh/day	12	9	2	25												
Lights, kWh/day	5.1	0.1	5.0	5.2	4	0.2	3	4	2	0.1	2	2	0.1	0.0	0.0	0.1
Feed motor, kWh/day	0.5	0.2	0.2	0.8	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.0	0.1	0.2
TOTAL, kWh/day	43	19	22	70	32	0	32	33	22	0	21	22	18	4	14	24
n for computing means (#of days)	6				7				5				6			
Pig Inventory		180				12				133				130		
Average mass, kg		250				250				20				30		
Total pig mass (kg)		45,000				3,000				2,660				3,900		

Note: The min, max, means, and standard deviation for all parameters measured were computed on a daily average. Average daily energy consumption was calculated by adding the 10-minute energy consumption in one day.

Table 4.14 and Figure 4.9 show that the grow-finish area had the highest contribution (44%) to total electrical energy consumption followed by farrowing at 26%, nursery at 18% and gestation at 12%. The grow-finish area consumed the most in terms of electrical energy which can be explained by its relative proportion in terms of production area compared to other stages (i.e. 59% grow-finish, 19% gestation, 11% farrowing, and 11% nursery). A relatively lower temperature set-point of about 19°C in the grow-finish room was also one of the reasons why higher electrical energy consumption was observed. All stages of fans were running to maintain this lower set-point to prevent heat stress on animals, thus, the fan operation required higher electrical energy. In farrowing rooms, the major energy consuming equipment were heat lamps, heat pads, and exhaust fans. In gestation and nursery rooms, exhaust fan was the main contributor to energy consumption.

Table 4.14 Estimated daily total electrical energy consumption (Barn B-summer)

	Gestation	Farrowing	Nursery	Grow-Finish	Barn Total
Electrical energy, kWh/room*	43	32	22	18	
No. of rooms	2	6	6	18	
Room Total	86	194	130	325	736

*kWh is computed based on the daily average values.

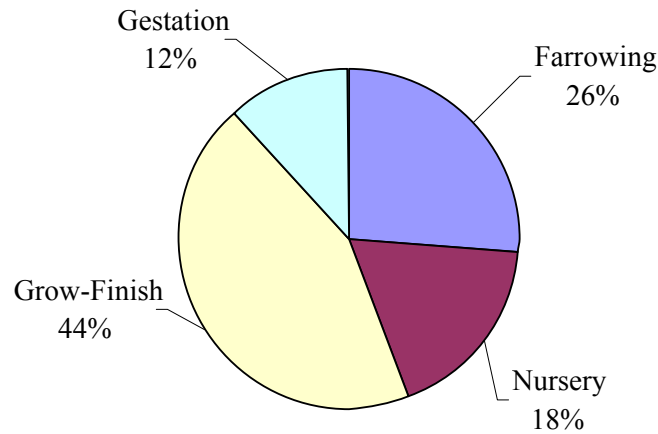
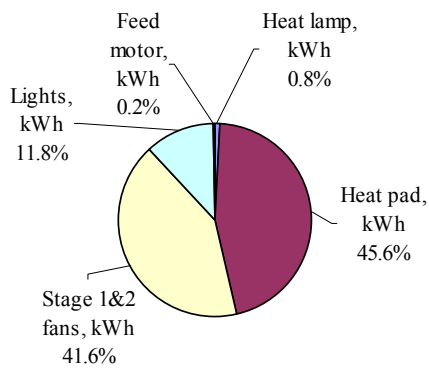


Figure 4.9 Percent distribution of electrical energy consumption (Barn B-summer)

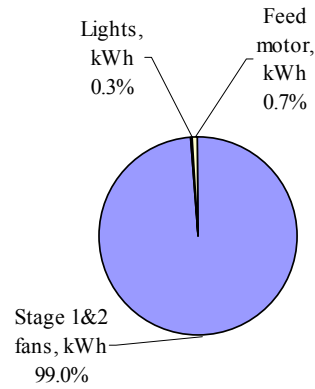
Table 4.15 and Figure 4.10 show that fan operations for the four rooms monitored had the highest electrical energy consumption during summer. The same observation was noted for barn A and this was attributed to the high ventilation rate associated with removing heat produced by the pig and heat transmission from the building and mechanical equipment inside the room. Another major contributor in the farrowing room was the heat pads (15%). Lights did not contribute much to the energy consumption because it was only turned on for 15 minute during inspection in farrowing, nursery, and grow-finish in this barn. However, in the gestation room where 14 hours of photoperiod was necessary for the estrus cycle of the sow, lighting was another area where improvement can be made.

Table 4.15 Daily average electrical energy consumption of various equipment in different production stages (Barn B-summer)

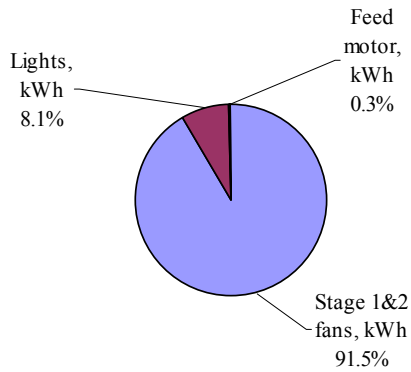
Equipment	Gestation	Farrowing	Nursery	Grow-Finish
Heat lamp, kWh/day	-	0.3	-	-
Heat pad, kWh/day	-	15	-	-
Stage 1&2 fans, kWh/day	13	13	20	18
Stage 3&4 fan, kWh/day	12	-	-	-
Stage 5&6, kWh/day	12	-	-	-
Lights, kWh/day	5	4	2	0.1
Feed motor, kWh/day	0.49	0.1	0.1	0.1
TOTAL, kWh/day	43	32	22	18



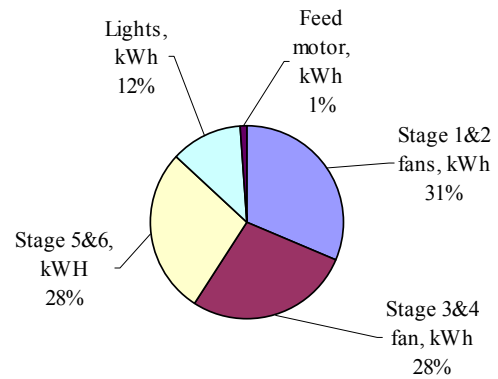
a. Farrowing Room



c. Grow-Finish Room



b. Nursery Room



d. Gestation Room

Figure 4.10 Percent contribution of various equipment to the daily average electrical energy consumption in different stages of production (Barn B-summer)

4.3.2.2.3 Winter Measurement in Barn B

Winter measurement for farrowing, gestation, nursery and grow-finish rooms in barn B was conducted in January 31st – February 7th, February 7th – 14th, February 14th – 21st, February 21st – 28th (2008), respectively. Table 4.16 shows the daily average, minimum and maximum values of parameters measured for all types of rooms.

The gas concentration measured in all monitored rooms was higher during winter than the measured values in summer due to reduced ventilation in winter to prevent cold draft. The electrical energy consumption per day in the farrowing, nursery, grow-finish and gestation rooms was 3.17 kWh/pig (1.27 kWh/100-kg pig), 0.12 kWh/pig (0.48 kWh/100-kg pig), 0.12 kWh/pig (0.35 kWh/100-kg pig) and 0.14 kWh/pig (0.06 kWh/100-kg pig), respectively.

Table 4.17 and Figure 4.11 show that the grow-finish area (18 rooms) had the highest contribution (43%) to total electrical energy consumption followed by farrowing at 35%, nursery at 14% and gestation at 8%. Grow-finish had the highest electrical energy consumption because of the relative size of this area compared to other production stages. The second highest electrical energy consumption was in farrowing operation because of the creep heating system (i.e. heat lamp and heat pad).

Table 4.16 Descriptive statistics for the parameters measured (Barn B-winter)

Parameters	Gestation				Farrowing				Nursery				Grow-Finish			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Outside temp, °C	-17	8	-28	-6	-16	7	-21	-4	-7	5	-13	0	-6	2	-8	-4
Room temp, °C	15	2	13	17	22	1	21	23	27	1	26	28	19	1	18	20
Set-point temperature, °C	19				21				28				19			
RH, %	63	1	62	66	55	2	52	58	68	3	63	71	59	1	57	61
H ₂ S, ppm	1	0	1	1	1	0	1	1	1	0.3	1	2	1	0	1	1
NH ₃ , ppm	6	0	6	6	6	0	5	6	7	0	7	8	2	0	2	2
CO ₂ , ppm	2,233	112	2,110	2,385	2,423	2,423	2,423	2,423	3,832	386	3,134	4,204	2,146	63	2,075	2,259
Heat lamp, kWh/day	-	-	-	-	6.3	4.0	0.2	10.9	-	-	-	-	-	-	-	-
Heat pad, kWh/day	-	-	-	-	16	5.4	8	22	-	-	-	-	-	-	-	-
Stage 1&2 fans, kWh/day	13	0	13	13	10	0.2	10	10	13	1.1	11	14	13	0	13	13
Stage 3&4 fan, kWh/day	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Stage 5&6, kWh/day	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lights, kWh/day	12.7	0.0	12.7	12.8	4	0.1	4	4	1	0.2	1	2	0.04	0.04	0.01	0.11
Feed motor, kWh/day	0.6	0.2	0.5	1.0	0.1	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.1	0.3
Recirculation pump, kWh/day	0	0	0	0	2.5	0.0	2.5	2.6	2	0	2	2	2	0	2	2
TOTAL, kWh/day	26	0	26	27	38	8	24	46	16	1	14	17	16	0	15	16
n for computing means (# of days)	6				6				6				6			
Pig Inventory		180				12				133				130		
Average mass, kg		250				250				25				35		
Total pig mass (kg)		45,000				3,000				3,325				4,550		

Note: The min, max, means, and standard deviation for all parameters measured were computed on a daily average. Average daily energy consumption was calculated by adding the 10-minute energy consumption in one day.

Table 4.17 Estimated daily total electrical energy consumption (Barn B-winter)

	Gestation	Farrowing	Nursery	Grow-Finish	Barn Total
Electrical energy, kWh/room*	26	38	16	16	
No. of rooms	2	6	6	18	
Room Total	53	230	94	279	657

*kWh is computed based on the daily average values.

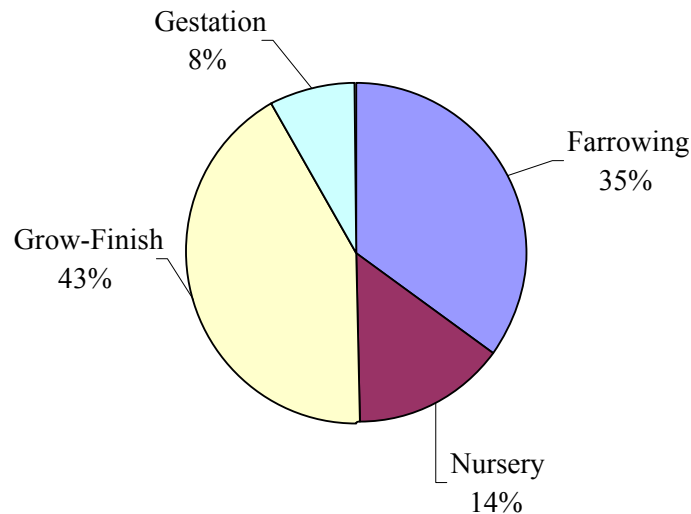


Figure 4.11 Percent distribution of electrical energy consumption (Barn B-winter)

Table 4.18 and Figure 4.12 show that stage 1 & 2 fans had the highest contribution to the energy use for all rooms. However, the operations of the fan have decreased during winter because of the reduced ventilation rate. Another area where improvement can be made was in creep heating where heat pads and heat lamps contributed 41% and 16.5% on total energy use, respectively. By implementing a strategy on creep heating system, which were discussed in detail in the simulation part of this study, significant reduction in energy cost can be attained.

Table 4.18 Daily average electrical energy consumption of various equipment in different production stages (Barn B-winter)

Equipment	Gestation	Farrowing	Nursery	Grow-Finish
Heat lamp, kWh/day	-	6.3	-	-
Heat pad, kWh/day	-	15.7	-	-
Stage 1&2 fans, kWh/day	13	9.9	13	13
Stage 3&4 fan, kWh/day	-	-	-	-
Stage 5&6, kWh/day	-	-	-	-
Lights, kWh/day	13	3.9	1	0.04
Feed motor, kWh/day	1	0.1	0.1	0.2
Recirculation pump, kWh/day	0	2.5	2	2
TOTAL, kWh/day	26	38.4	16	16

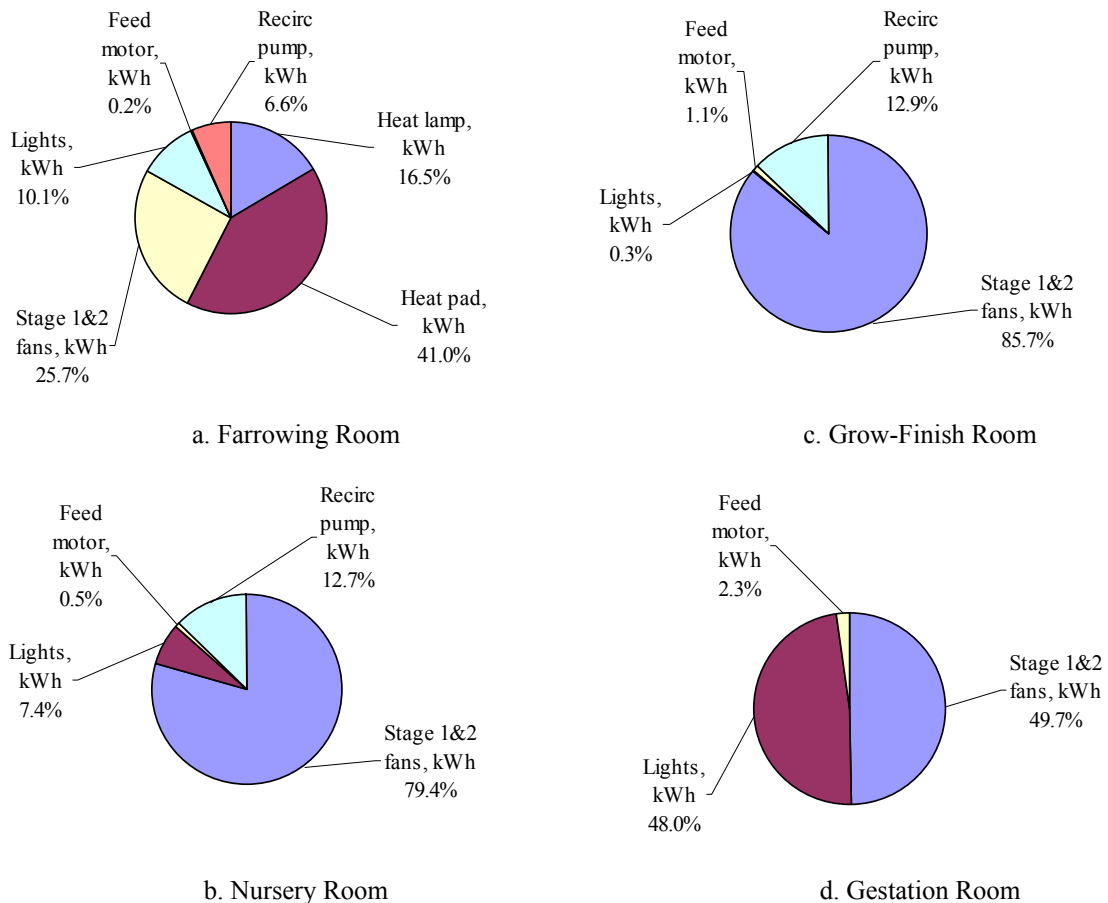


Figure 4.12 Percent contribution of various equipment to the daily average electrical energy consumption for different stages of production (Barn B-winter)

Table 4.19 and Figure 4.13 show the natural gas consumption for barn B. Among the four rooms monitored, nursery room had the highest energy consumption followed by the grow-finish room. This can be attributed to the high temperature set-point of 26 °C to 28°C in nursery rooms. Furthermore, the randomly selected room for grow-finish had 30-35 kg pigs during monitoring, thus resulting to a higher natural gas consumption because of a high temperature set-point. The natural gas consumption in gestation room was negligible since heat generated by the sows was sufficient to maintain the set-point temperature in the room. Outside temperature during measurement is shown in Table 4.16.

Table 4.19 Natural gas consumption for different production stages (Barn B-winter)

	Accumulated natural gas consumed for 7 days	
	m ³	MJ
Farrowing	56	2128
Nursery	91	3458
Grow-Finish	13	494
Gestation	0	0

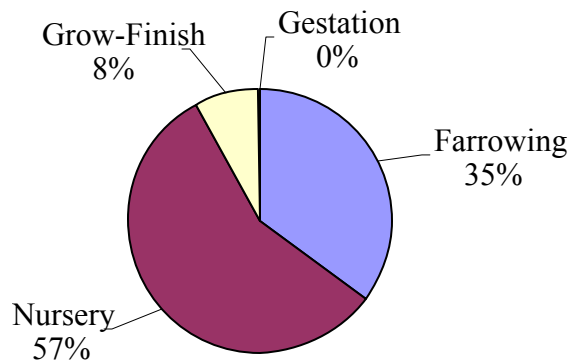


Figure 4.13 Percent distribution of natural gas consumption for different stages of production (Barn B-winter)

4.3.2.3 Barn C monitoring

4.3.2.3.1 Description of Barn C

Barn C was selected because it was one of the least efficient from the 28 surveyed barns. It is a 1,000-sow farrow-to-wean barn and has an average of 34,000 weanlings sold per year weighing an average of 7 kg each. The barn layout is shown in Figure 4.14. There were 11 farrowing rooms with 20 crates, 1 big gestation room with 532 sows, 1 gilt and 1 breeding room with 223 stalls each. Table 4.20 shows the equipment inventory in each type of room.

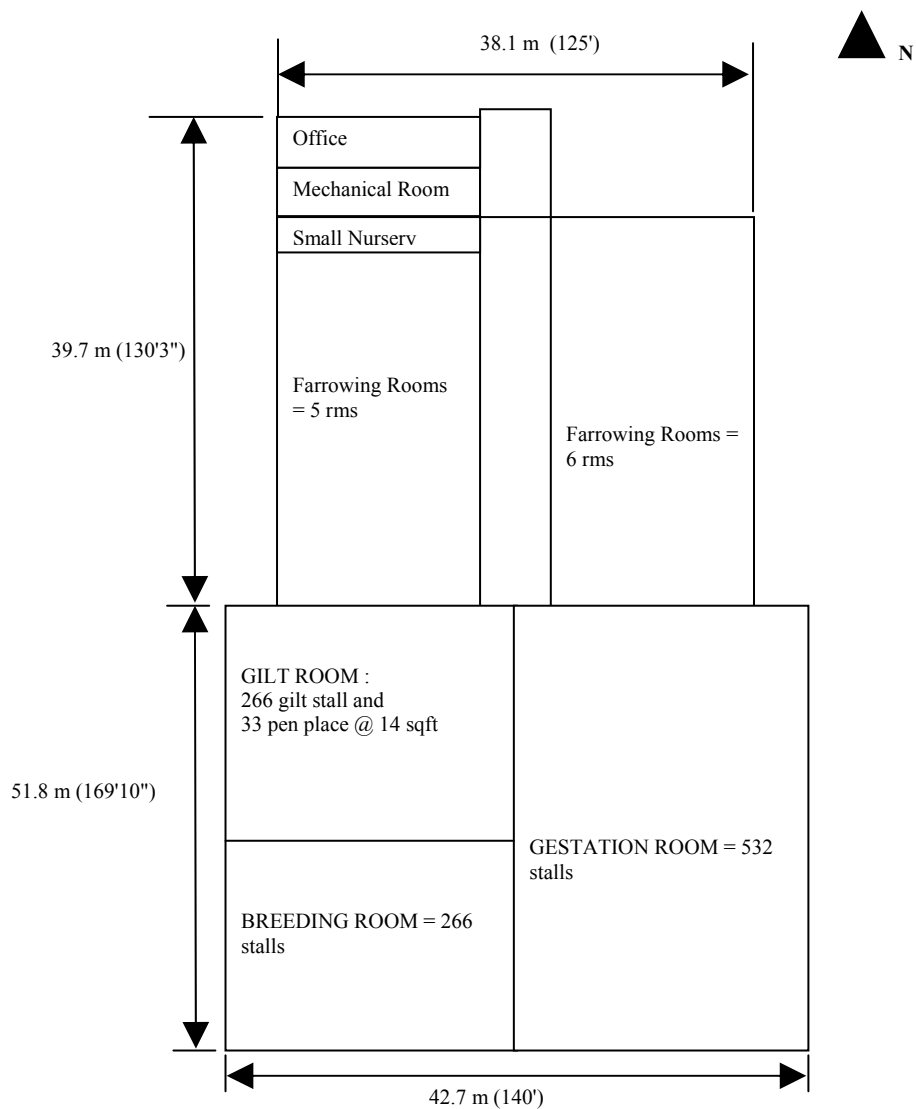


Figure 4.14 Layout of Barn C

Table 4.20 Equipment inventory in Barn C

Equipment	Farrowing Rooms	Gilt/Breed Rooms	Gestation Room
1. Lamp (T8) with 2 lamps per fixture	24 tubes	80 tubes	80 tubes
2. Feed motor	-	2 (0.5 hp)	8 (0.5 hp)
3. Exhaust fans (wall)	1 (1400 cfm) and 1 (2000 cfm)	1 (1800 cfm), 1 (2800 cfm), 1 (3600 cfm) and 2 (5000 cfm)	1 (1800 cfm), 1 (2800 cfm), 1 (3600 cfm) and 4 (5000 cfm)
4. Recirculation fans	-	2 (2000 cfm)	2 (2000 cfm)
5. Space heater (propane)	3 (80,000 BTUH)	2 (80,000 BTUH)	2 (80,000 BTUH)
6. Heat lamps (100 W)	20	-	-

4.3.2.3.2 Summer Measurement in Barn C

Summer measurement for farrowing and gestation in barn C was conducted in August 9th – 16th, August 16th – 23rd (2007), respectively. Table 4.21 shows the daily average, minimum and maximum values of parameters measured for all types of room. During summer measurement, higher H₂S, NH₃ and CO₂ concentration in farrowing room was observed compared to the other monitored rooms. This can be attributed to the animal activity, room temperature setting, and manure management. The electrical energy consumption per day in the farrowing and gestation rooms was 4.95 kWh/20 pig (2.2 kWh/100-kg pig), 0.36 kWh/532 pig (0.14 kWh/100-kg pig), respectively.

Farrowing area had the highest contribution to electrical energy as shown in Table 4.22 and Figure 4.15. Heat lamps were the main source for creep heat in this barn. As observed in other barns, another major contributing factor was fan operation which provided high ventilation during summer to maintain the set-point temperature with high outside temperature and other heat gain in the building. The farrowing area was 41% of the total production which had the highest energy consumption. This can be attributed to the creep heating system in farrowing room.

The electrical energy consumed by equipment in each monitored room is detailed and illustrated in Table 4.23 and Figure 4.16. Heat lamps contributed approximately 79% in the farrowing area

followed by lights (39%) and exhaust fans (16%). In gestation room, stages 1 to 6 exhaust fans were all running and contributed approximately 63% of the electrical energy consumption in gestation room. Set-point temperature in farrowing and gestation rooms was set at 20°C to prevent heat stress on the animals. To maintain this set-point temperature during summer, full operation of exhaust fans in all stages were required. This is the reason why exhaust fans were the major contributor to electrical energy consumption during summer.

Table 4.21 Descriptive statistics for the parameters measured (Barn C-summer)

Parameters	Gestation				Farrowing			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Outside temp, °C	18	2	14	21	16	3	12	19
Room temp, °C	21	1	20	22	22	1	22	23
Set-point temperature, °C	20				22			
RH, %	61	5	53	67	49	3	45	53
H ₂ S, ppm	1	1	1	2	1	0	1	1
NH ₃ , ppm	5	5	0	13	7	1	5	8
CO ₂ , ppm	692	59	650	734	1,180	72	1,049	1,228
Heat lamp, kWh/day	-	-	-	-	78	0.2	77	78
Stage 1&2 fans, kWh/day	49	0.3	49	50	16	4	9	19
Stage 3&4 fan, kWh/day	30	15	6	47	-	-	-	-
Stage 5&6 fan, kWh/day	37	30	0	68	-	-	-	-
Recirculation fan, kWh/day	35	0.2	35	36	-	-	-	-
Lights, kWh/day	38	7	34	52	4	0.2	4	4
Feed motor, kWh/day	2	0.5	2	3	1	0.1	1	1
TOTAL, kWh/day	192	40	144	231	99	3	92	102
n for computing means (# of days)	6				6			
Pig Inventory		532				20		
Average mass, kg		265				225		
Total pig mass (kg)		140,980				4,500		

Note: The min, max, means, and standard deviation for all parameters measured were computed on a daily average. Average daily energy consumption was calculated by adding the 10-minute energy consumption in one day.

Table 4.22 Estimated daily total electrical energy consumption (Barn C-summer)

	Gestation	Farrowing	Barn Total
Electrical energy, kWh/room*	192	99	
No. of rooms	2	11	
Room Total	383	1,085	1,468

*kWh is computed based on the daily average values.

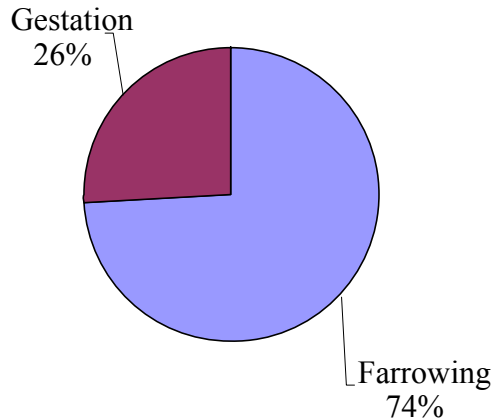


Figure 4.15 Percent distribution of electrical energy consumption (Barn C-summer)

Table 4.23 Daily average electrical energy consumption of various equipment in different production stages (Barn C-summer)

Equipment	Gestation	Farrowing
Heat lamp, kWh/day	-	78
Stage 1&2 fans, kWh/day	49	16
Stage 3&4 fan, kWh/day	30	-
Stage 5&6 fan, kWh/day	37	-
Recirculation fan, kWh/day	35	-
Lights, kWh/day	38	4
Feed motor, kWh/day	2	1
TOTAL, kWh/day	192	99

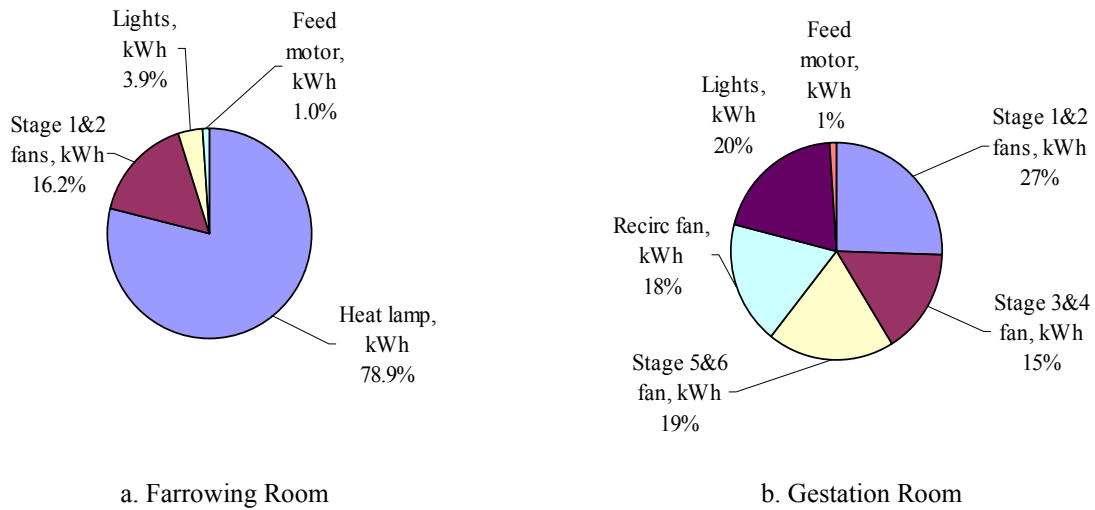


Figure 4.16 Percent contribution of various equipment to the daily average electrical energy consumption for different stages of production (Barn C-summer)

4.3.2.3.3 Winter Measurement in Barn C

Winter measurement for farrowing and gestation rooms in barn C was conducted in April 4th – 11th and March 28th to April 4th (2008), respectively. Table 4.24 shows the daily average, minimum and maximum values of parameters measured for all types of room. During the winter measurement for all rooms monitored, H₂S, NH₃ and CO₂ concentration observed was relatively higher than that measured during summer because of reduced ventilation in winter to prevent cold draft. The electrical energy consumption per day in the farrowing and gestation rooms was 3.95 kWh/20 pig (1.76 kWh/100-kg pig) and 0.25 kWh/525 pig (0.10 kWh/100-kg pig), respectively.

Table 4.24 Descriptive statistics for the parameters measured (Barn C-winter)

Parameters	Gestation				Farrowing			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Outside temp, °C	-5	4	-10	1	-2	4	-9	2
Room temp, °C	21	0	21	22	20	1	19	20
Set-point temperature, °C								
RH, %	50	1	48	52	45	3	40	49
H ₂ S, ppm	1	0	1	2	1	0	1	2
NH ₃ , ppm	8	1	7	10	10	1	9	11
CO ₂ , ppm	1,814	339	1,398	2,233	2,362	195	2,065	2,566
Heat lamp, kWh					59	2	54	60
Stage 1&2 fans, kWh	44	10	34	60	10	0	10	10
Recirculation fan, kWh	35	0.1	35	35				
Lights, kWh	54	0	54	54	4	1	4	5
Feed motor, kWh	3	0	3	3	2	0	1	2
Heater, kWh	0	0	0	0	4	3	1	9
TOTAL, kWh	136	10	127	153	79	3	77	83
n for computing means	6				6			
Pig Inventory		525				20		
Average mass, kg		260				225		
Total pig mass (kg)		136,500				4,500		

Note: The min, max, means, and standard deviation for all parameters measured was computed on a daily average. Average daily energy consumption was calculated by adding the 10-minute energy consumption in one day.

The highest contribution to electrical energy consumption in winter was farrowing area as shown in Table 4.25 and Figure 4.17. However, reduced ventilation had significantly decreased the electrical energy consumption for both farrowing and gestation rooms. Heat lamp was the major factor contributing to high energy consumption. The electrical energy consumption by various equipment in each monitored room is detailed and illustrated in Table 4.26 and Figure 4.18.

Table 4.25 Estimated daily total electrical energy consumption (Barn C-winter)

	Gestation	Farrowing	Barn Total
Electrical energy, kWh/room*	136	79	
No. of rooms	2	11	
Room Total	273	868	1,141

*kWh is computed based on the daily average values.

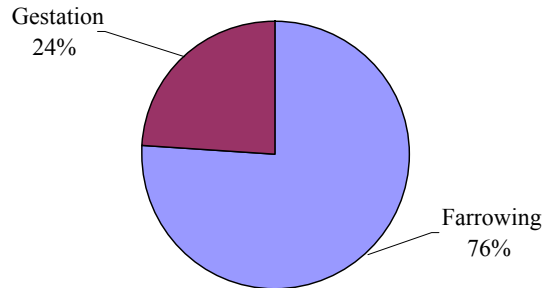


Figure 4.17 Percent distribution of electrical energy consumption (Barn C-winter)

Table 4.26 Daily average electrical energy consumption of various equipment in different production stages (Barn C-winter)

Equipment	Gestation	Farrowing
Heat lamp, kWh/day	0	59
Stage 1&2 fans, kWh/day	44	10
Stage 3&4 fan, kWh/day	0	0
Stage 5&6 fan, kWh/day	0	0
Recirculation fan, kWh/day	35	0
Lights, kWh/day	54	4
Feed motor, kWh/day	3	2
Heater, kWh/day	0	4
TOTAL, kWh/day	136	79

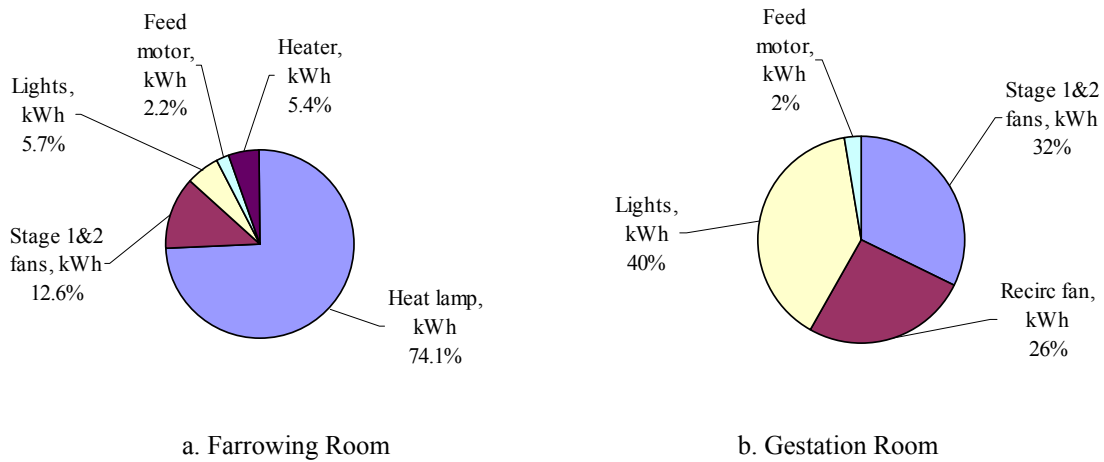


Figure 4.18 Percent contribution of various equipment to the daily average electrical energy consumption for different stages of production (Barn C- winter)

Table 4.27 and Figure 4.19 show the propane gas consumption for barn C. Among the rooms monitored, farrowing room had the highest energy consumption. The propane gas consumption in gestation room was negligible since heat generated by the sows was sufficient to maintain the set-point temperature in the room. The outside temperature during measurement is shown in Table 4.24.

Table 4.27 Natural gas consumption for different production stages (Barn C-winter)

	Accumulated natural gas consumed for 7 days	
	m ³	MJ
Farrowing	68	2,507
Gestation	0	0

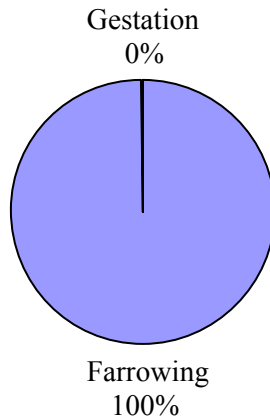


Figure 4.19 Percent distribution of natural gas consumption for different stages of production (Barn C-winter)

4.3.2.4 Barn D monitoring

4.3.2.4.1 Description of Barn D

Barn D was selected because it was one of the most efficient among the 28 surveyed barns. It is a grow-finish barn with an average of 30,000 pigs marketed per year at an average weight of 115 kg each. There were 8 grow-finish rooms with an average of 1,200 pigs per room. Table 4.28 shows the equipment inventory in each type of room. The barn layout is shown in Figure 4.20.

Table 4.28 Equipment inventory in Barn D

Equipment	Grow-Finish Rooms
1. Fluorescent lamp (T12) with 2 lamps per fixture	60 tubes
2. Feed motor	2 (1/2 hp) and 1 (1 hp)
3. Exhaust fans (wall)	1 (4410 cfm), 2 (6210 cfm), 3 (9067 cfm) and 3 (19900 cfm)
4. Distribution fans	1 (4410 cfm)
5. Space heater	4 (100,000 BTU)

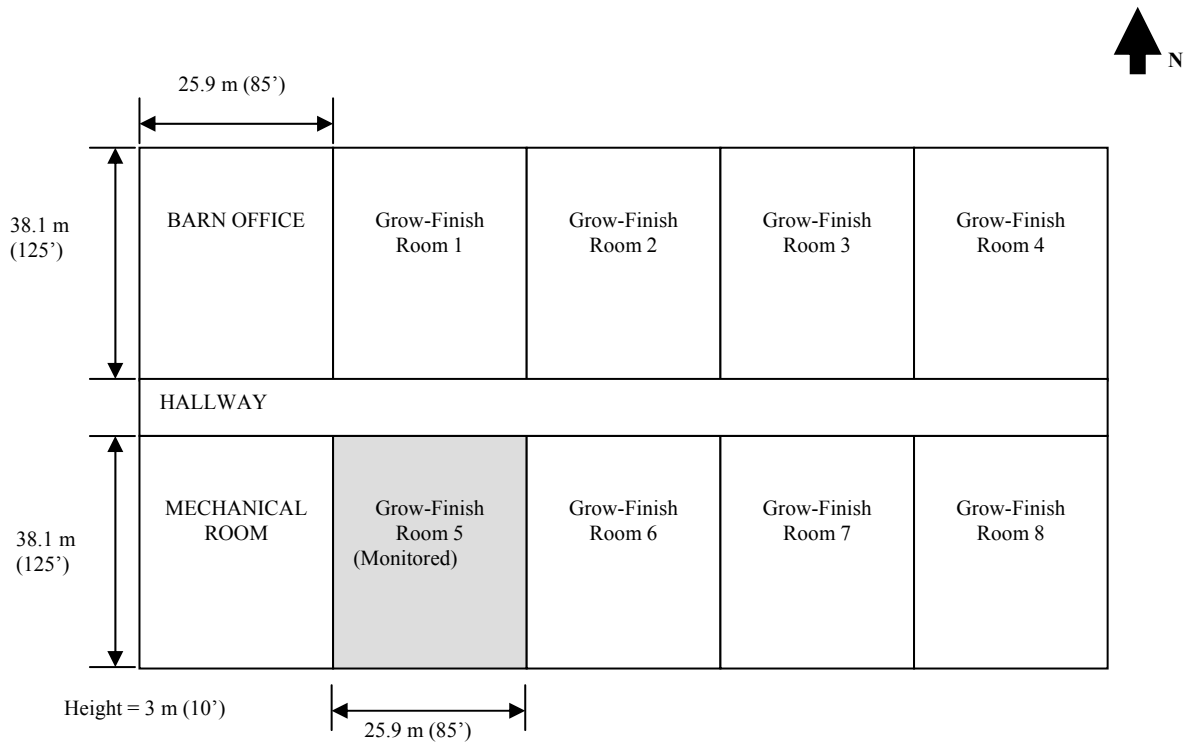


Figure 4.20 Layout of Barn D

4.3.2.4.2 Summer Measurement in Barn D

The summer measurement for grow-finish rooms in barn D was conducted in August 20th – 30th, 2007. Table 4.29 shows the daily average, minimum and maximum values of parameters measured. During the summer measurement in the grow-finish room, the average outside temperature was 14°C, room temperature was 21°C and relative humidity was 56%. Average H₂S, NH₃ and CO₂ concentration were 4 ppm, 25 ppm and 1214 ppm, respectively. Barn D has relatively high gas concentration compared to other barns which can be attributed to the pig capacity of one grow finish room (1,200 pigs). The stocking density is 1.2 pigs/m². The electrical energy consumption per day in the grow-finish room was 0.12 kWh/pig (0.19 kWh/100-kg pig).

Table 4.29 Descriptive statistics for the parameters measured (Barn D-summer)

Parameters	Grow-Finish			
	Min	Max	Mean	SD
Outside temp, °C	11	17	14	2
Room temp, °C	20	23	21	1.0
Set-point temp, °C	21			
RH, %	51	63	56	4.0
H ₂ S, ppm	3	6	4	1.0
NH ₃ , ppm	22	27	25	2.0
CO ₂ , ppm	1,004	1,422	1,214	132.3
Stage 0&1 fans, kWh/day	18	19	18	0.4
Stage 2 fan, kWh/day	23	49	40	7.5
Stage 3 fan, kWh/day	0	79	48	25.4
Lights, kWh/day	17	18	18	0.2
Feed motor, kWh/day	5	19	8	5.0
TOTAL, kWh/day	91	150	131	21.2
n for computing means (# of days)			9	
Pig Inventory		1,124		
Average mass, kg		60		
Total pig mass (kg)		67,440		

Note: The min, max, means, and standard deviation for all parameters measured were computed on a daily average. Average daily energy consumption was calculated by adding the 10-minute energy consumption in one day.

Figure 4.21 shows the contribution of fans, motors, and lights to the total daily electrical consumption in the room. This also illustrates that all fan stages were running which implied that high ventilation was required to remove heat gain from pigs and other sources. Fan operations contributed 81% to the total electrical energy consumption while lights and feed motor contributed 13% and 6%, respectively.

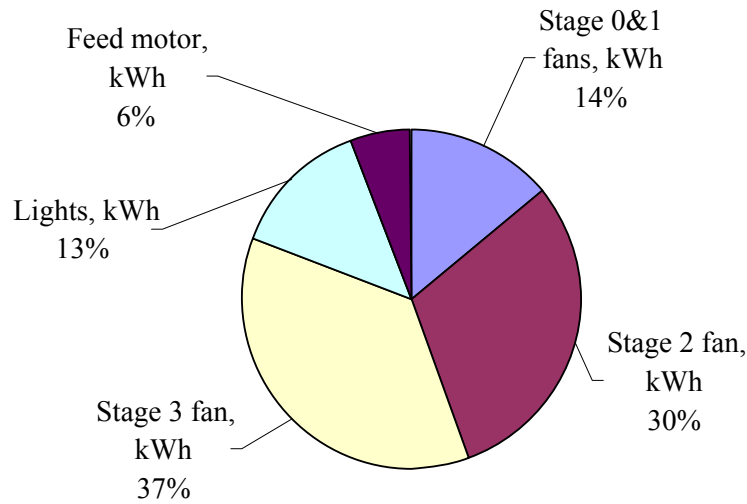


Figure 4.21 Percent contribution of various equipment to the daily average electrical energy consumption for different stages of production (Barn D-summer)

4.3.2.4.3 Winter Measurement in Barn D

Winter measurement for grow-finish rooms in barn D was conducted in February 12th – 19th, 2008. Table 4.30 shows the daily average, minimum and maximum values of parameters measured. During the monitoring period in the grow-finish room, the average outside temperature was -18°C , room temperature was 20°C and relative humidity was 57%. Average H_2S , NH_3 and CO_2 concentrations were 6 ppm, 21 ppm and 4286 ppm, respectively. Due to reduced ventilation in winter, the gas concentration had increased. Barn D had relatively high gas concentration in the room compared to other barns because of higher pig capacity. The electrical energy consumption per day in the grow-finish room was 0.07 kWh/1112 pig (0.10 kWh/100-kg pig).

Figure 4.22 shows that the fan operations contributed 65% to the total electrical energy consumption during winter which dropped from 81% contribution during summer. This can be attributed to the decreased ventilation rate during winter. The natural gas meter installed on the

heater for the room showed that the heater was not used over the seven consecutive days monitored. Also, there was no reading on the electrical current sensor for the heater blower, which means that the heat generated by 1,200 pigs inside the monitored room was sufficient to maintain the room at the set-point temperature of 19°C.

Table 4.30 Descriptive statistics for the parameters measured (Barn D–winter)

Parameters	Grow-Finish			
	Min	Max	Mean	SD
Outside temp, °C	-28	-2	-18	9
Room temp, °C	18	21	20	1.066
Set-point temp, °C	19			
RH, %	50	64	57	5.2
H ₂ S, ppm	5	6	6	0.594
NH ₃ , ppm	21	21	21	0.5
CO ₂ , ppm	4,173	4,399	4,286	159.7
Stage 0&1 fans, kWh/day	18	19	19	0.6
Stage 2 fan, kWh/day	23	39	29	5.349
Stage 3 fan, kWh/day				
Lights, kWh/day	18	20	19	0.429
Feed motor, kWh/day	5	13	7	2.9
Heater, kWh/day	0	0	0	0
TOTAL, kWh/day	66	82	73	5.2
n for computing means (# of days)			6	
Pig Inventory		1,112		
Average mass, kg		65		
Total pig mass (kg)		72,280		

Note: The min, max, means and standard deviation for all parameters measured was computed on a daily average. Average daily energy consumption was calculated by adding the 10-minute energy consumption in one day.

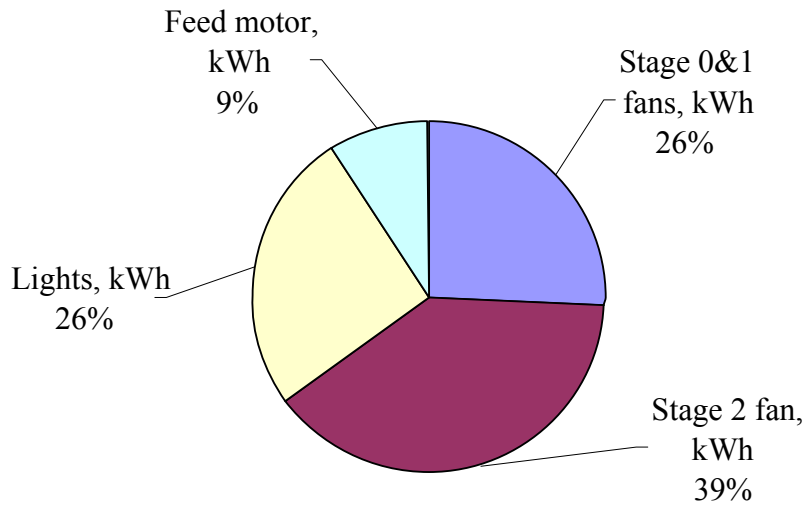


Figure 4.22 Percent distribution of electrical energy consumption (Barn D-winter)

4.3.2.5 Correlation between fan energy consumption and indoor air quality

Ventilation affects the level of gas (i.e. NH₃, H₂S and CO₂) concentration in the room. The goal of correlating the two factors was to determine if management practices and strategies had compromised the animal's welfare in an attempt to reduce energy consumption. Using SAS v.9.1 proc corr, correlation between fan energy consumption and indoor air quality was determined and the results are shown in Table 4.31. The statistical analysis for correlation is shown in Appendix D.

Table 4.31 Correlation coefficient of fan energy consumption and indoor air quality during summer and winter

Parameters	Barn A				Barn B				Barn C		Barn D
	F	N	GF	G	F	N	GF	G	F	G	GF
SUMMER											
H ₂ S	-0.7	-0.7	-0.6	-0.7	-0.9	-0.9	-0.6	-0.7	-0.6	-0.7	-0.9
NH ₃	-0.8	-0.8	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.7	-0.6	-0.8
CO ₂	-0.7	-0.9	-0.9	-0.6	-0.6	-0.7	-0.6	-0.8	-0.7	-0.8	-0.9
WINTER											
H ₂ S	-0.1	-0.4	-0.1	-0.4	-0.1	-0.5	-0.1	-0.1	-0.1	-0.6	-0.1
NH ₃	-0.4	-0.7	-0.1	-0.4	-0.1	-0.1	-0.2	-0.2	-0.1	-0.6	-0.1
CO ₂	-0.2	-0.2	-0.1	0.3	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1

Note: F- farrowing, N-nursery, GF- grow-finish and G-gestation

During summer and winter, fan electrical energy consumption and indoor air quality had a negative correlation. High ventilation rate increased the electrical energy consumption of the fan. The negative correlation implied that the higher ventilation rate, the lower the concentration of noxious gases. There was a medium to high correlation for fan energy consumption and indoor air quality in different production rooms for all barns during summer but weak to medium correlation during winter. The weak correlation during winter can be attributed to the constant minimum ventilation set during winter. Minimum ventilation was set during winter to prevent cold draft. As a result of this, the change in ventilation in relation to the change in IAQ parameters was very small, thus, lower correlation was observed during winter.

Table 4.32 shows that the combined results of winter and summer resulted to better correlation coefficient. A more defined relationship between the fan energy consumption and IAQ parameters was observed. However, the same conclusion that there was a negative correlation between fan energy consumption and indoor air parameters can be derived from the following data.

Table 4.32 Correlation coefficient of fan energy consumption and indoor air quality

Parameters	Barn A				Barn B				Barn C		Barn D
	F	N	GF	G	F	N	GF	G	F	G	GF
H ₂ S	-0.6	-0.8	-0.8	-0.6	-0.5	-0.7	-0.5	-0.6	-0.7	-0.7	-0.5
NH ₃	-0.8	-0.6	-0.6	-0.5	-0.6	-0.5	-0.5	-0.5	-0.8	-0.6	-0.7
CO ₂	-0.5	-0.8	-0.7	-0.6	-0.6	-0.6	-0.6	-0.8	-0.5	-0.7	-0.6

This observed correlation between fan energy consumption and noxious gases concentration implied that simply reducing ventilation rate is not a sound option because it would increase concentration of gases which can be hazardous to animals and barn workers. It also showed that proper ventilation design (i.e. designing the stages of fan operations, etc) should be implemented for barns that have higher gas concentration even when all stages of fan are running. Reducing energy cost should not compromise the health of the animals and the workers in the barn.

4.4 Summary

The result of the summer measurement on electrical energy consumption was summarized in Table 4.33, which shows that there is a wide variation in the actual electrical energy consumed in each stage of production for all the barns monitored. This can be attributed to the differences in management practices employed in each barn. In farrowing rooms, Barn C has the highest electrical energy consumption followed by Barns A and B. This can be explained by the different strategies applied for creep heating. Barn C used heat lamps only while Barns A and B used heat pads in combination with heat lamps. Furthermore, Barn A used heat lamps for 72 hours before and after farrowing while Barn B used lamps for 24 hours after farrowing. The differences in equipment used and their efficiencies also contributed to the variation in energy consumption for all barns. Barn A, B and D used T12 lamps while Barn C used a more energy efficient T8 lamps. There were also differences in cfm/W rating of the exhaust fans. Exhaust fans are the major contributor to energy usage during summer. Choosing a higher cfm/W rating can significantly reduce the energy consumption.

Table 4.33 Average daily electrical energy consumption for four barns in summer

Rooms Monitored	Barn A		Barn B		Barn C		Barn D	
	kWh per head	kWh per 100-kg	kWh per head	kWh per 100-kg	kWh per head	kWh per 100-kg	kWh per head	kWh per 100-kg
Farrowing	3.75	1.63	2.67	0.40	4.95	2.2	-	-
Nursery	0.08	0.33	0.16	0.83	-	-	-	-
Grow-Finish	0.17	0.25	0.14	0.46	-	-	0.12	0.19
Gestation	0.40	0.16	0.24	0.10	0.36	0.14	-	-

The result of the winter measurement on electrical energy consumption was summarized in Table 4.34, which shows that the average daily electrical energy consumption in grow-finish and gestation rooms for all barns has decreased compared to that in summer. This can be explained by reduced ventilation during winter. Furthermore, the heat generated by the pigs in the grow-finish and gestation rooms was sufficient to maintain the room's set-point temperature. On the other hand, an increase in electrical energy consumption was observed in the farrowing rooms for Barns A and B. This can be explained by the longer operation of heat lamps in combination with the heat pads during winter measurement in these barns. Operation of heat lamps greatly depended on the management practices and barn staff availability. Heat lamps on Barns A and B

was plugged in and out manually. Heat lamps on Barn A were set up prior to farrowing while those in Barn B were set when the sows already farrowed. For nursery room in barn A, the increase in electrical consumption can be attributed to the operation of the heater, which operated almost continuously during winter in nursery room due to high set-point temperature required for pig's comfort.

Table 4.34 Average daily electrical energy consumption for four barns in winter

Rooms Monitored	Barn A		Barn B		Barn C		Barn D	
	kWh per head	kWh per 100-kg	kWh per head	kWh per 100-kg	kWh per head	kWh per 100-kg	kWh per head	kWh per 100-kg
Farrowing	4.64	2.02	3.17	1.27	3.95	1.76	-	-
Nursery	0.16	0.63	0.12	0.48	-	-	-	-
Grow-Finish	0.09	0.13	0.12	0.35	-	-	0.07	0.10
Gestation	0.28	0.11	0.14	0.06	0.25	0.10	-	-

Table 4.35 shows the accumulated gas consumption for seven days during winter in four monitored barns. The results showed that grow-finish and gestation required less or no supplemental heat during the measurement period. Nursery had the highest consumption in terms of energy consumed per 100-kg pig due to higher animal activity and high room temperature setting. Higher animal activity generated contaminants that need to be removed through ventilation. This resulted to increased volume of cold incoming air, thus, requiring additional supplemental heat. This implied that significant reduction in gas consumption can be achieved if it was applied on the nursery area.

Table 4.35 Accumulated gas consumption for seven days in four barns during winter

Rooms Monitored	Barn A		Barn B		Barn C		Barn D	
	MJ per head	MJ per 100-kg	MJ per head	MJ per 100-kg	MJ per head	MJ per 100-kg	MJ per head	MJ per 100-kg
Farrowing	134.44	58.45	177.33	66.92	125.35	55.71	-	-
Nursery	41.00	164.01	26.12	366.2	-	-	-	-
Grow-Finish	-	-	3.80	3.45	-	-	-	-
Gestation	0.65	0.26	-	-	-	-	-	-

A negative correlation between the fan electrical energy consumption and indoor air quality parameters was determined for winter and summer seasons in all barns. Medium to high correlation (range -0.6 to -0.9) was observed during summer and weak to medium correlation

(-0.1 to -0.7) for winter. The negative correlation indicated that the higher the fan electrical energy, the lower the gas concentration. It follows that the higher the ventilation rate, the higher the fan electrical energy consumed. In summer, the ventilation rate was high and thus gas concentration was low as the stale air from barn was exhausted through the fans at a faster rate. During winter, a constant minimum ventilation rate to remove contaminants was required. For the 7-consecutive day measurement, a relatively constant ammonia and hydrogen sulphide was observed. Thus, correlation between the two parameters was weak. Using the combined winter and summer data on fan energy consumption and IAQ parameters, the same results with that in summer was observed.

5 EVALUATION OF ENERGY CONSERVATION MEASURES USING SIMULATION

5.1 Introduction

Evaluation of energy conservation measures can be done by in-barn experiment or building simulation. The high cost of conducting in-barn experiments limits the options of researcher to evaluate different energy-conservation measures. On the other hand, simulation can determine and evaluate the impact of various strategies at minimal cost. The disadvantage of using simulation was that the underlying assumptions can be a major source of error. Another disadvantage was the required technical knowledge to do the simulation. In this study, various energy-saving strategies were evaluated through simulation using mathematical model. The principles of heat and mass transfer and law of thermodynamics (conservation of energy) were used to develop the model. Other computer simulation programs (i.e. eQuest, DOE2, and Transys) were based on residential or commercial buildings that have airspace with positive pressure. Bantle and Barber (1989) used DOE2 in simulating energy consumption in poultry barns and the results showed a good fit between the predicted and actual values. However, typical swine barns have exhaust fans creating negative pressure inside the building, thus, the model used in that study would not be applicable to swine barn. In this study, the algorithm used took into account the exhaust fan, space heater, creep heater, pigs as occupants, and the 24-hour occupant schedule. The data measured and information gathered (i.e. building characteristics, occupant, equipment inventory, and schedule of equipment run-time gathered) from the four selected barns during benchmarking were used to develop and validate the model. The objective of this part of the study was to evaluate energy conservation measures that can be applied in swine barns to reduce overall energy cost.

5.2 Methodology

5.2.1 Model development

Heat transfer in a building can be analyzed by focusing on internal features and examining the processes in detail or through the control volume approach. Because the overall goal of this simulation was to develop a model and create a baseline case to which energy conservation strategies were applied, simplifying assumptions were made to predict energy savings. Thus, the control volume approach (black box), which is a powerful tool despite its excessive simplification of the process in the system (Albright, 1990), was used in this study to develop the model. In this approach, only the processes that pass through the boundary were examined. The control volume for energy balance was the air inside the room in which the energy consumption was desired, bounded by the walls, floor, and ceiling as shown in Figure 5.1. The following simplifying assumptions for control volume approach which were used in this study are:

- a) air temperature in the adjacent rooms were relatively the same as the room being simulated;
- b) attic temperature was the same as the outside temperature;
- c) there were no radiation heat fluxes between the interior surfaces and between the animal and the surfaces; and
- d) there was complete mixing of air, thus, temperature in all surfaces was the same.

The first assumption was made because the simulated room and the adjacent rooms have the same temperature set-point, construction materials, animal capacity, and stage of production. In the previous research conducted by Li (2000), the same assumption was made. The simulated room in that study was a grow-finish room located in between other grow-finish rooms. The results showed that the predicted and actual values have small difference, thus, supporting the validity of this assumption. Furthermore, the heat transfer through internal walls of the simulated room and the hallway were not considered because it was also assumed that these areas have relatively the same temperature. Only external walls, ceiling, and floor were considered in the computation of heat transmission through building components.

Calculations were made on heat transmission through the roof affected by solar radiation and other meteorological conditions during winter and summer. The percentage of the heat gain through the ceiling was relatively small compared to the heat gain from animals during summer. Additionally, the percentage heat loss through the ceiling was relatively small compared to the heat loss through ventilation (Li, 2000). This supports the assumption to consider attic temperature to be the same as the outside temperature and the ceiling as boundary layer for the control volume.

In a simulation study on dynamic thermal environment (Li, 2000), it was assumed that there is no radiation heat fluxes between the surfaces and between the animal and the surfaces. This means that all heat generated and loss in the room were instantaneous. The radiation heat flux between surfaces was convected to the air on a 24-hour basis (ASHRAE, 2005). Since the main goal of this study was to simulate the entire production area for a year, the average heat gain can be assumed to be instantaneous, thus, supporting the third assumption.

A research study on computer simulation (Ogilvie et al., 1988) assumed that the air in the simulated unit was completely mixed such that the temperature of the exhaust air is always equal to the average room temperature. Although, this simplifying assumption can be a great source of error in the simulation, it was observed in previous studies (Bantle and Barber, 1989; Ogilvie et al., 1988; Li, 2000) that there was a good fit between the actual and predicted values. Recirculation fans were used to attain a completely mixed air in the room, although, in real conditions this was not possible. However, the average room temperature and exhaust air temperature would have a relatively small difference due to air recirculation. Thus, the fourth assumption was made.

Based on research conducted by Barber (1991) on the design of heating and ventilation in cold climate, it was revealed that the total heat loss or heat gain through the building shell was much smaller than that through ventilation. However, to accurately account for all sources of heat gains and losses, heat transmission through the external walls, ceiling and floor perimeter were considered in this study.

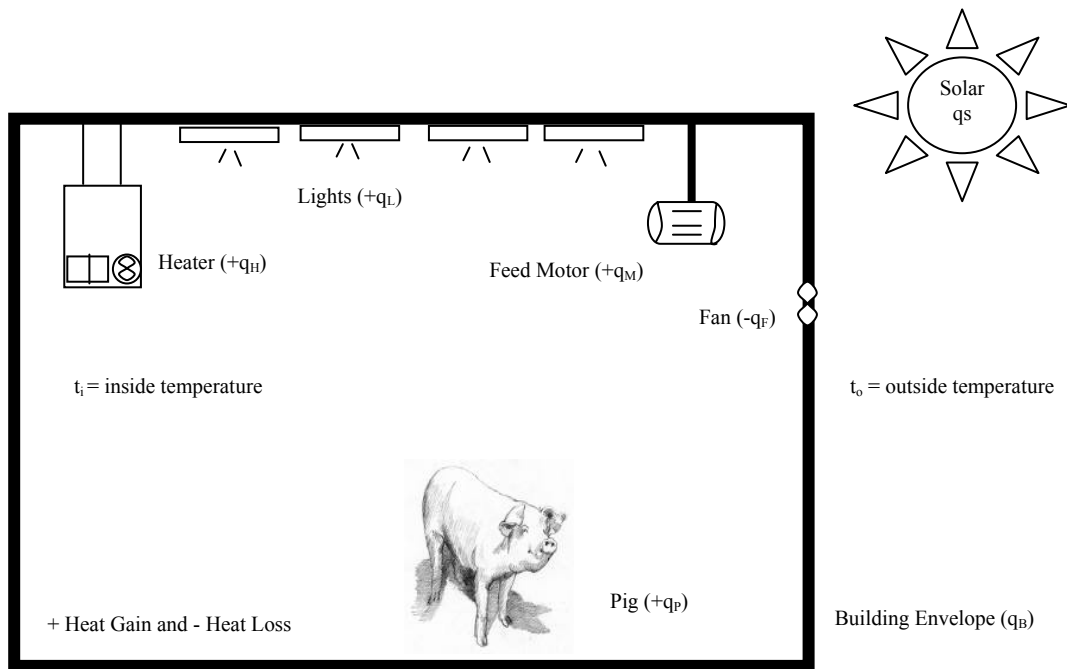


Figure 5.1 Heat gains and heat losses in a swine production room

5.2.2 Heat balance for the control volume approach

The information on building characteristics, occupants, equipment inventory, and schedule of equipment run-time gathered from the four (4) selected barns were used as input to simulate the heat generation and heat transfer processes in the barn building. The model was developed using the principles of heat transfer and the law of conservation of energy.

The law of conservation of energy states that the sum of net heat supplied to the system and the net work done by the system is equal to zero. This implies that in a closed system, the sum of energy gains is equal to the sum of energy losses. Typical sources of heat gains and losses in a swine production room are shown in Figure 5.1.

The general mathematical model used in this study is as follows:

$$\text{Heat gain} = \text{Heat loss} \quad (5.1)$$

$$q_P + q_L + q_M + q_H = q_B + q_F \quad (5.2)$$

where:

q_P is the total heat generated by the pigs, W

q_L is the heat generated by the lights, W

q_M is the heat generated by the feed motors, W

q_H is the supplemental heat from the heater, W

q_B is the heat loss through building, W

q_F is the heat loss through ventilation fans, W

Direct solar radiation (q_s) entering the swine building was not included in equation 5.2 because generally swine barns do not have windows. However, solar radiation increased the building surface temperature which affected the heat transmission through the external walls. Furthermore, q_H was assumed to be zero during warm weather condition because the heater was not needed during this period. Sample calculations for each heat gain and loss are shown in Appendix G from sections G.1.1 – G.1.3.

5.2.3 Total heat generated by the pigs

Based on ASAE D270.4 and Brandl et al. (2004), the following equation was used in this study to determine the total heat generated by pigs. Previous studies showed that the effect of ambient temperature to which the pigs are exposed to and the mass of the pig had significant effect on the total heat production.

$$THP = 10^{[(1.189 - (0.005 * t)) - (0.345 * (\log m))]} \quad (5.3)$$

where:

THP is the total heat production by the pigs, W

t is the indoor air temperature, °C

m is the weight of the pigs determined from barn records, kg

Total animal heat generated by the pigs varied diurnally (Pedersen, 2002). Since feeding was done during the day, animal activity was observed to be higher during this time. With increased activity, total animal heat generated increases. Pedersen (1996) and Blane and Pedersen (2005) conducted a study on heat and moisture production for pigs. The significant result of that study was the development of animal activity correction factor (A). This correction factor considered the time of the day with minimal activity (h_{\min}) and the time of the day in 24-hour clock (h) as shown in the following sinusoidal equation.

$$A = 1 - a \sin \left[\left(\frac{2\pi}{24} \right) x (h + 6 - h_{\min}) \right] \quad (5.4)$$

Measurements by Pedersen (1996) showed that the minimum activity occurs at 2 a.m. (h_{\min}) and that the diurnal variation for pig houses were approximately 20% ($a = 0.20$). Applying the constant a and h_{\min} on the previous equation, hourly correction factor for animal heat dissipation can be computed and thus accounted for the diurnal variations of the heat generated by the pigs.

5.2.4 Heat generated by the lights

The instantaneous rate of heat gain from electric lighting was computed based on the following equation (ASHRAE, 2005).

$$q_L = W F_u F_s \quad (5.5)$$

where:

q_L is the heat gain from lights, W

W is the total light wattage, W

F_u is the lighting use factor (generally has a value of 1.0 for commercial application)

F_s is the lighting special allowance factor (account for ballast losses)

The total light wattage is the rating of the lamps while the lighting special allowance factor is specified in ASHRAE handbook chapter 30 based on type of lamp and ballast.

5.2.5 Heat generated by the feed motors

Contribution of electric motors to heat gain can be computed using the following equation (ASHRAE, 2005).

$$q_m = (P_m / E_m) F_l F_u \quad (5.6)$$

where:

q_m is the heat equivalent of equipment operation, W

P_m is the motor power rating, W

E_m is the motor efficiency, as decimal fraction < 1.0

F_l is the motor load factor, generally has a value of 1.0

F_u is the motor use factor, 1.0 or decimal fraction < 1.0

Motor use factor was applied for motors which were used intermittently such as feed motor. Feed motors were generally used for less than 10 minutes at certain time of the day. In this study, motor use factor was based on hourly operation of the motor (i.e. F_u is zero if motor is not used for the hour or given a value less than 1.0 for percentage of the hour it was running). For instance, if the motor was operated for 10 minutes at 2 p.m., the motor use factor is 0.17 for that hour. Heat output of motor was proportional to the motor load and due to typically high no-load motor current and fixed losses; motor load factor was generally assumed to be unity if not specified by manufacturer.

5.2.6 Heat transmission through the building components

The total heat loss through the building components included the heat transmission through the wall, ceiling, and floor. This can be computed using equation 5.7.

$$q_b = q_w + q_c + q_f \quad (5.7)$$

where:

q_b is the total building heat transmission, W

q_w is the heat transmission through the external wall, W

q_c is the heat transmission through the ceiling, W

q_f is the perimeter heat loss through the floor, W

5.2.6.1 Heat loss through the external walls

Prior to computing the heat transmission through an external wall, sol-air temperature was first determined. Sol-air temperature is the equivalent outdoor air temperature that, in the absence of all radiation changes, gives the same rate of heat entry into the external wall surface. The calculation of the sol-air temperature is shown in Appendix E. The heat transmission through the external wall can be computed using the following equation.

$$q_w = UA_s (t_e - t_i) \quad (5.8)$$

where:

q_w is the heat transmission through the walls, W

U is the thermal transmittance representing the overall heat transfer coefficient, $W/m^2 K$

A_s is the surface area, m^2

t_i is the indoor air temperature (C or K)

t_e is the sol-air temperature (C or K)

The U-value of the building component has an inverse relationship with unit area thermal resistance ($U = 1/R_T$). Thermal resistance to heat flow was composed of different boundary layers. This included the indoor air film, construction materials and outdoor air film as shown in the following equation.

$$R_T = R_i + R_n + R_o \quad (5.9)$$

where:

R_T is the total thermal resistance to heat flow, $m^2 \text{ K/W}$

R_i is the thermal resistance of indoor air film, $m^2 \text{ K/W}$

R_n is the thermal resistance of n layer, $m^2 \text{ K/W}$

R_o is the thermal resistance of outdoor air film, $m^2 \text{ K/W}$

Thermal resistance (R_n) for n layers 1, 2 and 3 as shown in Figure 5.2 is a function of the thickness (Δx) and conductivity (k) of the construction materials and is expressed using the following equation.

$$R_n = \frac{\Delta x_n}{k_n} \quad (5.10)$$

where:

R_n is the thermal resistance of the n layer, $m^2 \text{ K/W}$

Δx_n is the thickness of the construction material n, m

k_n is the thermal conductivity of the construction material n (ASHRAE, 2005), W/m K

Direction of heat flow is always from the location with high temperature to that with a lower temperature. This determines whether the heat transmission through the building envelope is a heat gain or heat loss in a control volume approach. The construction materials of the simulated barn were obtained from the building's blueprint and are shown in Table G.1 (Appendix G) while the properties of construction materials can be found on ASHRAE (2005).

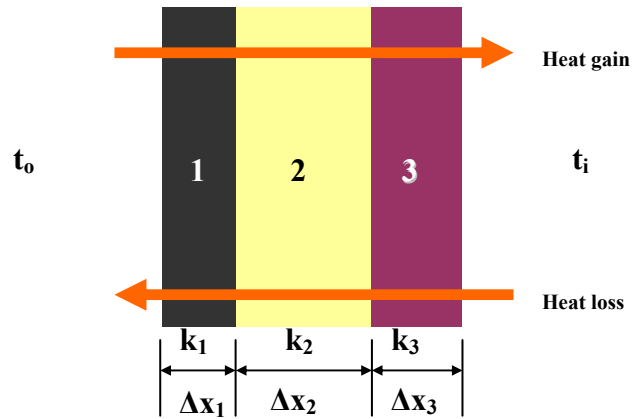


Figure 5.2 Heat transfer through building envelope

Thermal resistance for indoor/outdoor air film (R_o and R_i) was computed using the convective heat transfer coefficient.

$$h = \frac{Nu \cdot \lambda_a}{x} \quad (5.11)$$

where:

h is the thermal resistance through convection ($h = 1/R$), $W/m^2 K$

Nu is the Nusselt number, dimensionless

λ_a is the air conductivity, $W/(m \cdot K)$

x is the characteristic length (i.e. height of the wall or width of ceiling), m

Research conducted by Zhang (1989) used an average Nusselt number in the estimation of convective heat transfer coefficients at building surfaces with an underlying assumption that the air movement along the building's inside surface was treated as laminar flow on a flat surface.

$$Nu_l = 0.664 Re^{1/2} Pr^{1/3} \quad (5.12)$$

Reynolds number can be computed using the following equation:

$$\text{Re} = \frac{wx}{\nu} \quad (5.13)$$

where:

w = air flow velocity, m/s

x is the characteristic length (i.e. height of the wall or width of ceiling), m

ν = kinematic viscosity, m²/s

Prandtl number has different values for varying air temperature. At air temperature of – 40°C to 40 °C (range of outside temperature in Saskatchewan), the Pr is approximately 0.7 for air. Incorporating the Reynolds and Prandtl numbers, the following equation for the Nusselt number can be rewritten as:

$$\text{Nu} = 0.590 \left(\frac{wx}{\nu} \right)^{1/2} \quad (5.14)$$

The average air velocity within the airspace was assumed to be 0.3 m/s (Li, 2000). This assumption was verified in this study. This was based on the required recirculation system for the room and was verified by computing the airflow rate (m³/s) provided by all recirculation fans divided by the area (m²) of recirculation duct in all types of room monitored for all barns. The outside convective heat transfer coefficient, h_o , was treated as a constant because it has little effect on the dynamics of heat transfer inside the control volume (Zhang, 1989). A design value of h_o for winter and summer at specified wind speed can be found in ASHRAE handbook chapter 25.

5.2.6.2 Heat loss through the ceiling

The heat transmission through the ceiling can be computed using the following equation.

$$q_c = UA_s (t_o - t_i) \quad (5.15)$$

where:

q_c is the heat transmission through the ceiling, W

U is the thermal transmittance representing the overall heat transfer coefficient, $W/m^2 K$

A_s is the surface area, m^2

t_i is the indoor air temperature, C or K

t_o is the attic temperature, which is assumed to be equal to outdoor temperature, C or K

5.2.6.3 Perimeter heat loss through the floor

The heat transmission through the floor perimeter was relatively minimal (Albright, 1990). However, to account for all heat losses, the perimeter heat loss was included in the calculation in this study. The heat transmission through floor is expressed as:

$$q_f = F \cdot P \cdot (t_o - t_i) \quad (5.16)$$

where:

q_f is the perimeter heat loss, W

F is the perimeter heat loss coefficient based on insulation (ASHRAE, 2005), W/m

P is the perimeter length of exposed edges, m

t_i is the inside air temperature, K

t_o is the outside air temperature, K

5.2.7 Heat loss through ventilation fans

The heat loss through the exhaust fans during winter was computed using the following equation.

$$q_F = \rho V C_p (t_o - t_i) \quad (5.17)$$

where:

q_F is the heat loss through ventilation fans, W

ρ is the density of air, kg/m³

V is the ventilation rate using ventilation graph, m³/s

C_p is the specific heat of air, J/kg-K

t_i is the inside air temperature (set-point temperature), K

t_o is the outside air temperature, K

The ventilation graph, which shows the ventilation rate at different outdoor temperature, was created by computing for the minimum ventilation rate in winter and maximum ventilation rate in summer using equation 5.23. Sample calculations are shown in sections G.1 and G.2 of Appendix G.

5.2.8 Calculation of electrical energy consumption of equipment in the room monitored

5.2.8.1 Lights, heat lamps, heat pads, motor and recirculation fans

Energy consumption for the lights (E_L), heat lamps (E_{HL}), heat pads (E_{HP}), feed motors (E_M), recirculation fan (E_{RF}), are relatively constant throughout the year. Computation of consumption for this equipment was done using equations 5.18 – 5.22. The results were then compared to the actual electrical energy consumption measured during the energy audit. The number of equipment, power rating, hours of use and efficiency were determined from barn inventory and manufacturer's specifications.

$$E_L = \# \text{ of fixtures} * \text{fixtures/lamp} * \text{power rating} * \text{hours of use} \quad (5.18)$$

$$E_{HL} = \# \text{ of heat lamps} * \text{power rating} * \text{hours of use} \quad (5.19)$$

$$E_{HP} = \# \text{ of heat pads} * \text{power rating} * \text{hours of use} \quad (5.20)$$

$$E_M = \# \text{ of motors} * \text{power rating} * \text{efficiency} * \text{hours of use} \quad (5.21)$$

$$E_{RF} = \# \text{ of recirculation fans} * \text{power rating} * \text{efficiency} * \text{hours of use} \quad (5.22)$$

The exhaust fan electrical energy consumption and heater gas consumption are dependent on the heat gain and heat loss inside the swine production room.

5.2.8.2 Exhaust fans

To compute for the fan electrical energy consumption, the previous mathematical model for heat balance was applied using equation 5.2. The ventilation rate (cfm) required to remove the net heat gain inside the building during summer was computed using the following equation (Albright, 1990).

$$V_f = \frac{q_P + q_L + q_M - q_b}{1006 \rho_{air} (t_i - t_o)} \times 2118 \quad (5.23)$$

where:

V_f is the ventilation rate, cfm

q_P is the heat generated by pigs, W

q_L is the heat generated by lights, W

q_M is the heat generated by feed motors, W

q_b is the heat transmission through building component, W

t_i is the inside air temperature, C or K

t_o is the outside air temperature, C or K

The ventilation rate was determined using the ventilation graph developed for all monitored rooms in the simulated barn. Sample calculation in generating the ventilation graph is shown in Appendix G. The inside temperature used in calculating the maximum ventilation rate during summer was the temperature set to activate all fan stages. This information can be obtained from the fan manufacturer and from the HVAC design. The outside design temperature used was obtained from ASHRAE (2005) at 2% cooling dry bulb temperature during warm weather. During winter, the inside temperature used was the set-point temperature for each room while the outdoor design temperature used was the extreme condition at 99% heating dry bulb temperature (ASHRAE, 2005). The annual weather data for Saskatoon used was obtained from Environment Canada and is shown in Appendix F.

From the ventilation rate, exhaust fan electrical energy consumption (E_F) in kilowatts was computed. This was done by determining the number of fans that operated per stage, fan capacity, and fan efficiency as shown in the following equation. The ventilation rate required was matched to the different fan stages and fan capacity to determine if the specific stage of fan was operated. The fan capacity and fan efficiency can be obtained from the manufacturer's specification.

$$E_F = \frac{(V_f / \text{fan efficiency})}{1000} \quad (5.24)$$

where:

V_f is the ventilation rate, cfm

Fan efficiency, cfm/W

5.2.9 Calculation of gas consumption of space heater in the room monitored

The gas consumed by the heaters was computed based on the same law of heat transfer and energy balance. The net heat gain inside the building was determined first if supplemental heat is required or not. If the net heat is negative, then supplemental heat is needed. Otherwise, the space heater would not be operated, therefore, no gas consumption would be expected. The gas

consumed by the heater (F_h) was then computed based on the heater efficiency (η), heating value of the fuel used (HV) as shown in the following equation (McQuiston, et. al, 2005).

$$F_h = \frac{\{[(q_F + q_B) - (q_P + q_L + q_M)]/t\} * 3.6}{\eta HV} \quad (5.25)$$

where:

F_h is the fuel consumed by the heater, m^3

q_F is the heat loss through ventilation fans, W

q_b is the heat transmission through building component, W

q_P is the heat generated by pigs, W

q_L is the heat generated by lights, W

q_M is the heat generated by feed motors, W

t is the per unit time, hour

η is the heater efficiency, decimal

HV is the heating value of the fuel used, MJ/ m^3 (i.e. natural gas = 35; propane = 94)

5.2.10 Application of simulation model on swine barn

5.2.10.1 Room simulation and validation

The room simulation was done per production stage on an hourly basis over a 24-hour period. A spreadsheet (Excel ®) was developed to carry out the calculations using the equations described in previous sections. The inputs for the spreadsheet were building location (i.e. latitude and longitude); room size; wall, ceiling, and floor construction and R-values; number and weight of pigs; and equipment specifications and operating hours. Room simulation was done for summer and winter conditions for different production stages in four barns monitored. Weather data from the different barn locations was used to compute for the simulated energy consumption of fans and heaters. Electrical energy consumption for lights, heat lamps, heat pads, recirculation fans, and feed motors were computed using equations 5.18 to 5.22. In the computation of electrical energy consumption of exhaust fans, ventilation rate required in winter and summer was first determined by using the ventilation graph. A sample calculation is shown in section G.1 of Appendix G.

Validation of the mathematical model involves determining how close the simulated values to the actual parameters measured. Percent difference between simulated and actual values was computed using equation 5.26 (Van Dyke et al., 2007). The mathematical model was considered validated when percent difference from the measured energy consumption is equal to or less than 10%.

$$\% \text{ difference} = \frac{|V_a - V_p|}{\left(\frac{V_a + V_p}{2}\right)} \times 100 \quad (5.26)$$

where:

V_a is the actual measured energy consumption, kWh or MJ

V_p is the simulated energy consumption, kWh or MJ

5.2.10.2 Simulation of the annual energy consumption: baseline case

A baseline case was needed to determine the level of energy use on an existing building. Energy-conservation strategies were applied to this baseline in order to quantify energy saving associated with implementing that strategy.

Barn A is a farrow-to-finish barn, which represents 55% of typical barns in Saskatchewan (SaskPork, 2007). This barn was selected for building simulation on an annual basis since it was the least energy efficient among the surveyed and monitored barns, therefore, significant improvements on this barn can be made.

Typically, the hours of use for lights, feed motors, recirculation fans, heat lamps, and heat pads were relatively constant throughout the year. Thus, a straight forward calculation of the electrical energy consumed by these equipment was done using equations 5.18 to 5.22.

For the exhaust fans and natural/propane gas heaters, the calculation of the energy consumption was done using the mathematical model (equation 5.2). Weather data in Saskatoon was obtained from Environment Canada and the hourly average temperature from day 1 to day 365 over 5-year period were computed (Appendix F). The model was implemented through a spreadsheet. The ventilation graph for each room in Barn A was developed through heat balance. The maximum ventilation in summer and the minimum ventilation in winter were required to create the ventilation graph. After the relationship between outdoor temperature and ventilation rate was determined from the ventilation graph, the corresponding electrical energy consumption was computed. Sample calculations were discussed in Appendix G.

5.2.10.3 Application of energy-conservation strategies to the baseline case

Different conservation strategies were applied to the baseline case for different areas such as lighting, creep heating, space heating, and ventilation. The strategies chosen were divided into two groups, namely, set A and B strategies. The set A strategies were the most obvious and easy to adopt strategies. This includes using energy efficient lighting system, fans, feed motor, and

creep heating system. Set B strategies were measures that were not so easy to implement but can be viable options when the market conditions are favorable. This includes the use of heat exchanger and radiant heater. The details on how each strategy was implemented were discussed in subsequent section.

5.3 Results and Discussion

5.3.1 Model Validation

The model was validated by comparing the predicted and actual energy consumption in various barns in different locations within the province with different ambient conditions and barn management practices.

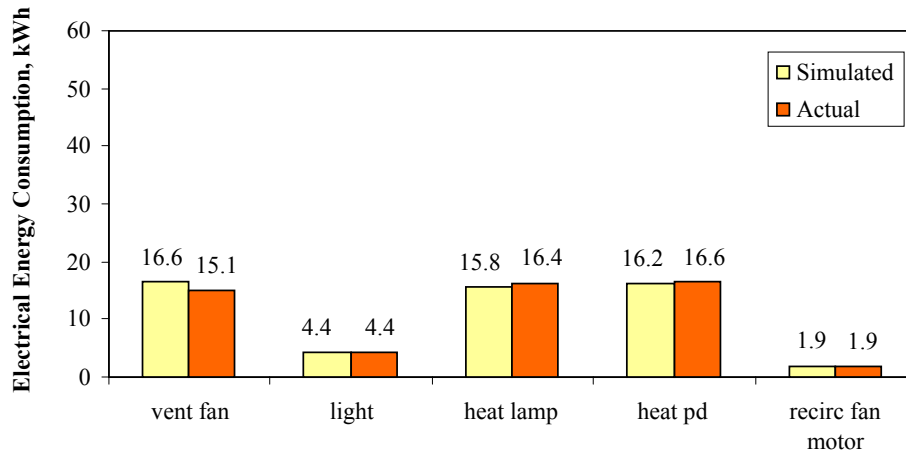
5.3.1.1 Model Validation for Barn A

The results of model validation for Barn A are shown in Figures 5.3 to 5.6. In the farrowing room monitored, the percent difference between the simulated and actual electrical energy consumption measured during summer for ventilation fan, light, heat lamp, heat pad and recirculation fan were 9.1%, 0.8%, 3.8%, 2.2% and 1.8%, respectively. The percent difference between the simulated and actual electrical energy consumption measured during winter for ventilation fan, light, heat lamp, heat pad, and recirculation fan were 4.9%, 6.5%, 1.5%, 9.0% and 11.2%, respectively. The simulated and actual natural gas consumption had a percent difference of 6.4%.

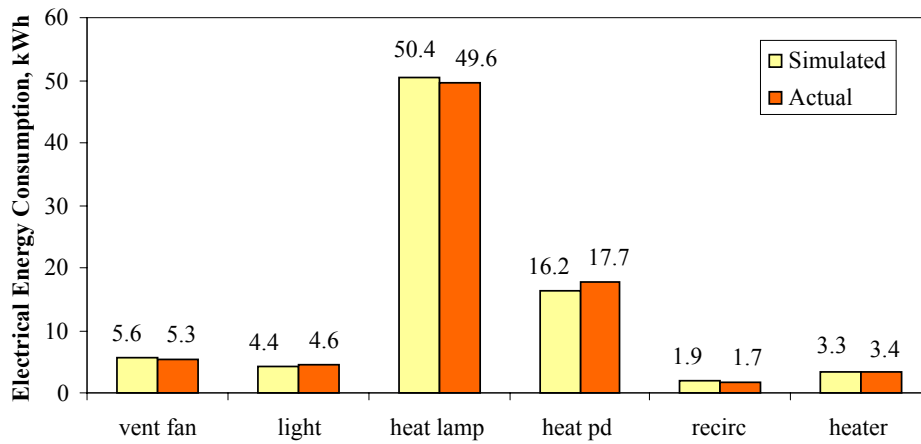
In nursery room monitored, the percent difference between the simulated and actual electrical energy consumption during summer for ventilation fan, light, motor and recirculation fan were 11.1%, 6.3%, 3.3% and 3.6%, respectively. The percent difference between the simulated and actual electrical energy consumption during winter for ventilation fan, light, motor and recirculation fan are 6.5%, 7.4%, 8.8% and 10.4%, respectively. The simulated and actual natural gas consumption had a percent difference of 7.3%.

In grow-finish room monitored, the percent difference between the simulated and actual electrical energy consumption during summer for ventilation fan, light, and motor were 11.8%, 1.3%, and 1.9%, respectively. The percent difference between the simulated and actual electrical energy consumption during winter for ventilation fan, light, and motor were 8.5%, 5.4% and 1.8%, respectively. There was no natural gas consumption measured during the monitoring period because the heat generated by the pigs was sufficient to maintain the indoor temperature at the set-point. The calculated net heat gain is positive which means that there was no supplemental heat needed, thus the simulated gas consumption was also zero.

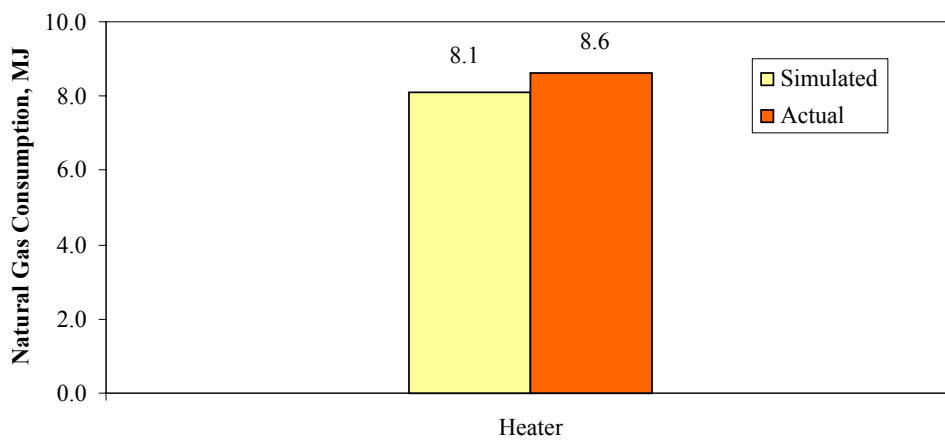
In gestation room monitored, the percent difference between the simulated and actual electrical energy consumption during summer for ventilation fan, light, and motor were 5.9%, 10.7%, and 5.6%, respectively. The percent difference between the simulated and actual electrical energy consumption during winter for ventilation fan, light, and motor were 7.7%, 3.1%, 10.1% and 7.9%, respectively. The simulated and actual natural gas consumption had a percent difference of 20.41%. The relatively high percentage difference on natural gas consumption for the gestation room can be attributed to the number of heaters and the gas meters installed on the room. For farrowing, nursery, and grow-finish rooms, there was only one space heater to which the gas meter was installed. Since the heaters were controlled by the same device using the temperature sensor in the room, only one of the three heaters in gestation room was monitored due to limited instrument. Therefore, it was assumed that the operation of the other two heaters were the same as the one monitored, which can be a source of error.



a. Electrical energy consumption in summer

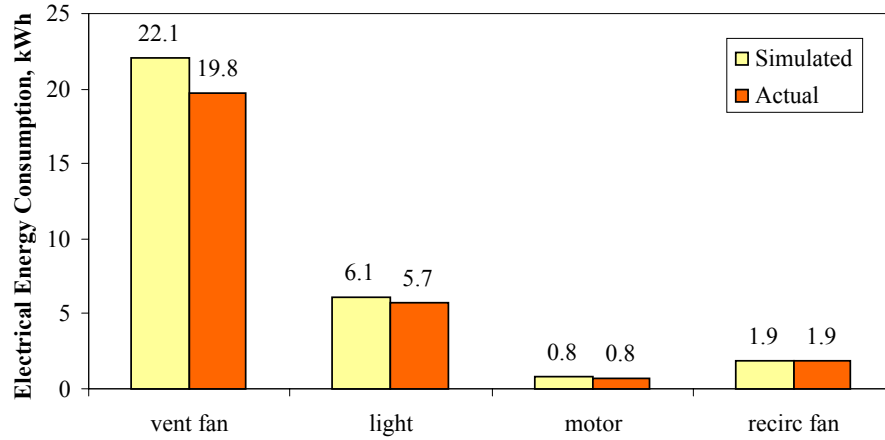


b. Electrical energy consumption in winter

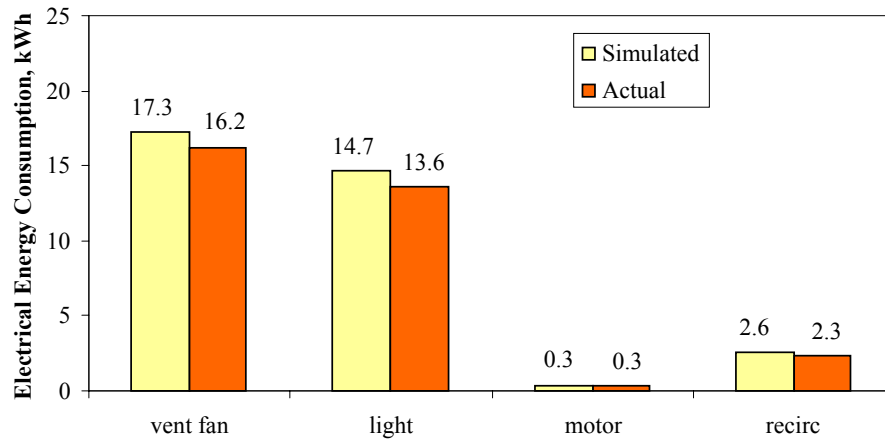


c. Natural gas consumption in winter

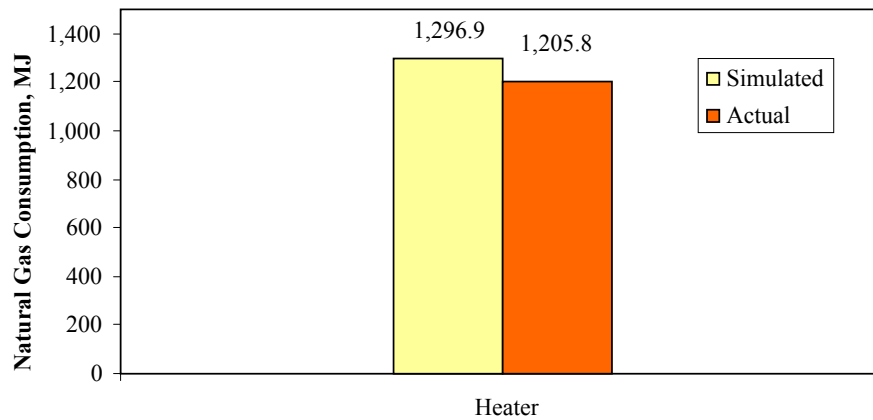
Figure 5.3 Simulated and actual energy consumption in farrowing room (Barn A)



a. Electrical energy consumption in summer

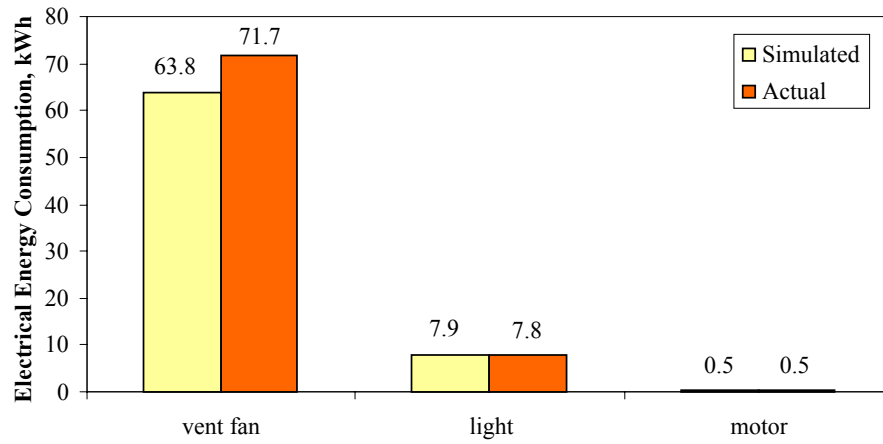


b. Electrical energy consumption in winter

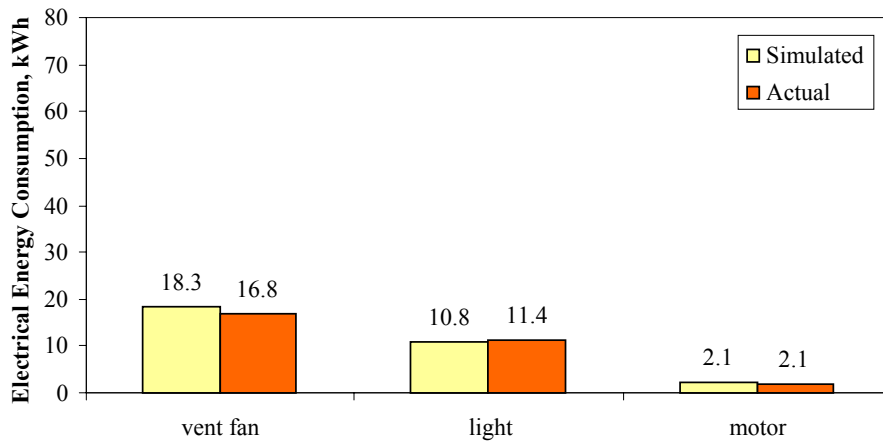


c. Natural gas consumption in winter

Figure 5.4 Simulated and actual energy consumption in nursery room (Barn A)

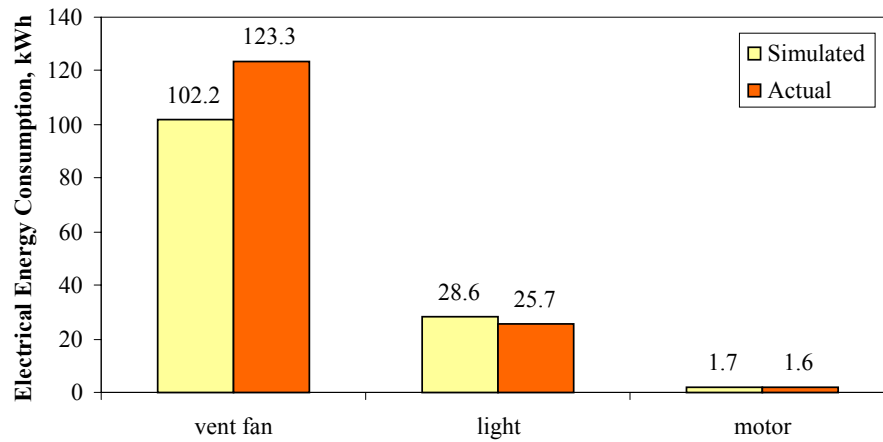


a. Electrical energy consumption in summer

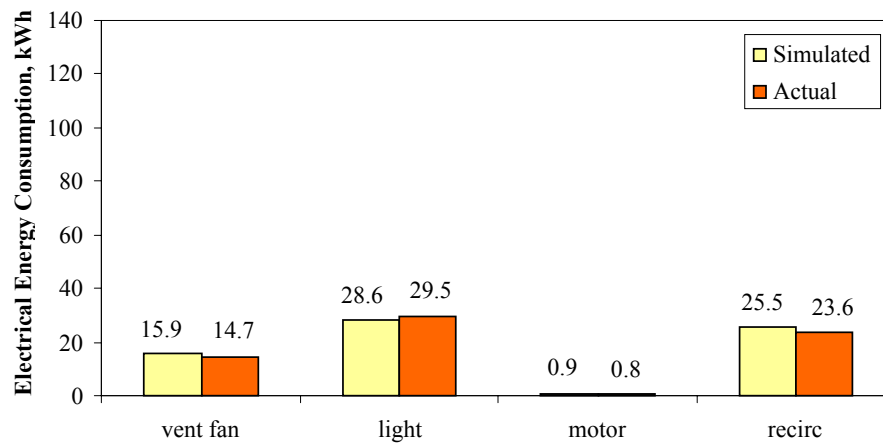


b. Electrical energy consumption in winter

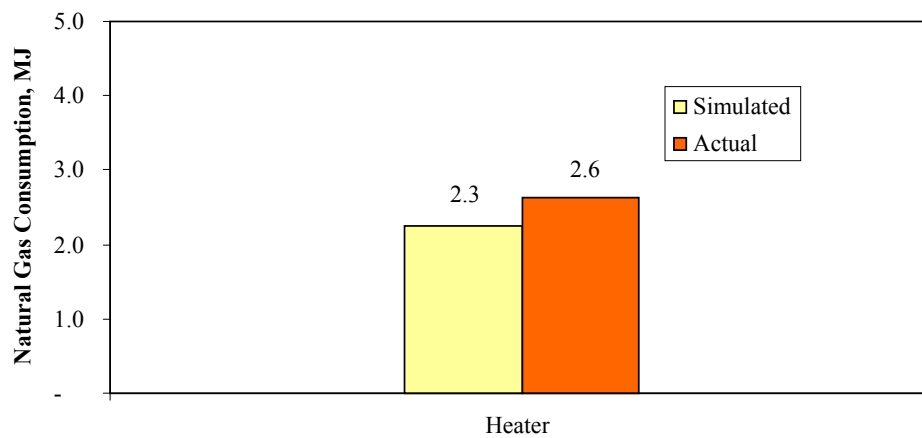
Figure 5.5 Simulated and actual electrical energy consumption in grow-finish room (Barn A), No gas consumption



a. Electrical energy consumption in summer



b. Electrical energy consumption in winter

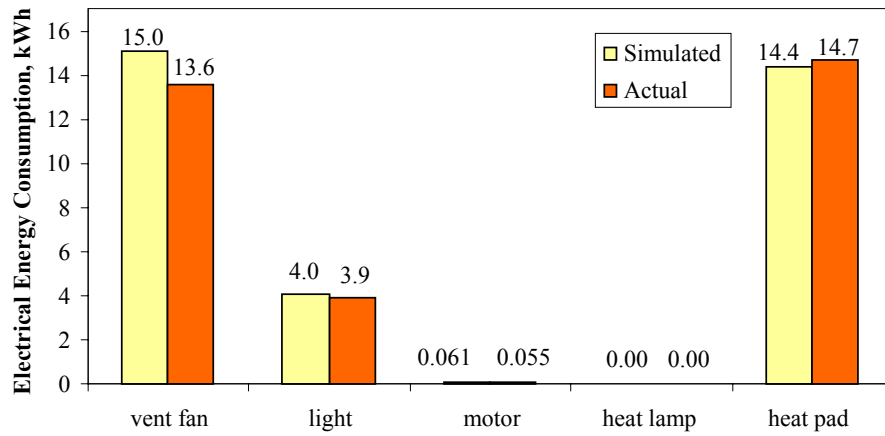


c. Natural gas consumption in winter

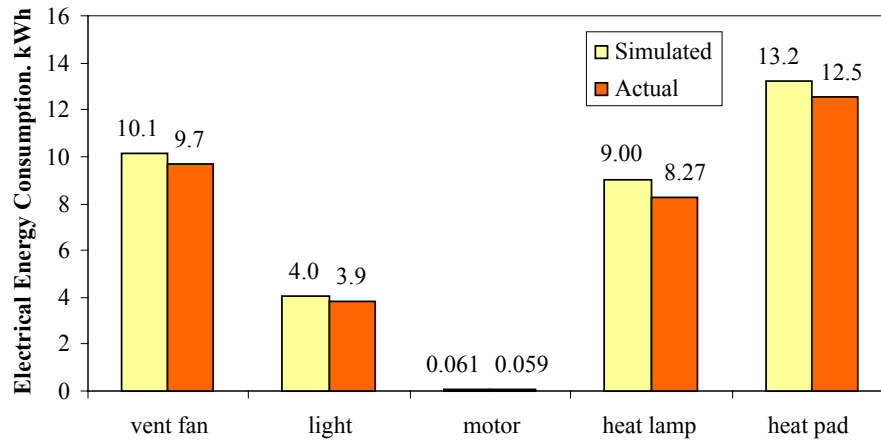
Figure 5.6 Simulated and actual energy consumption in gestation room (Barn A)

5.3.1.2 Model Validation for Barn B

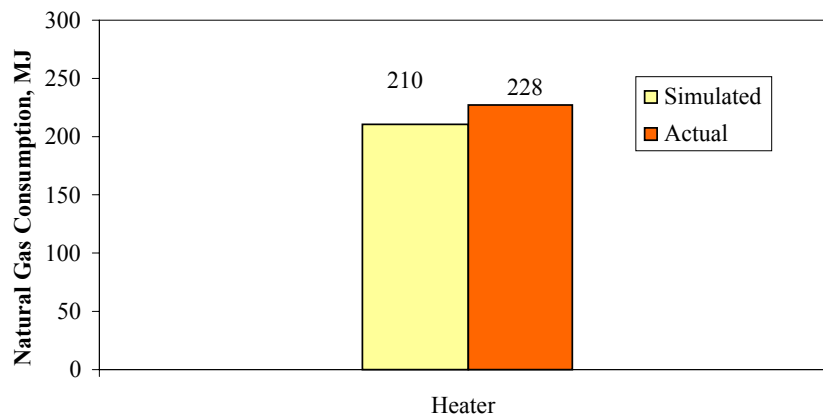
The results of model validation for Barn B are shown in Figures 5.7 to 5.10. In farrowing room monitored, the percent difference between the simulated and actual energy consumption measured during summer for ventilation fan, light, motor, and heat pad were 10.2%, 2.4%, 10.4%, and 1.8%, respectively. There was no reading obtained on heat lamp because the lamp was turned off 24 hours after farrowing. The percent difference between the simulated and actual electrical energy consumption measured during winter for ventilation fan, light, motor, heat lamp and heat pad were 4.8%, 4.4%, 3.0%, 8.4% and 5.3%, respectively. The simulated and actual natural gas consumption had an 8.2% difference. In nursery room, the percent difference between the simulated and actual energy consumption measured during summer for ventilation fan, light, and motor were 2.7%, 2.9% and 9.6%, respectively. The percent difference between the simulated and actual electrical energy consumption measured during winter for ventilation fan, light, and motor were 10.5%, 5.8 % and 10.8%, respectively. The simulated and actual natural gas consumption had a 15.9% difference. The gas meter measured consumption in six rooms, thus, a higher percentage difference was observed when simulated value was compared with the actual value. In grow-finish room, the percent difference between the simulated and actual electrical energy consumption measured during summer for ventilation fan, light, and motor were 12.7%, 9.3% and 10.4%, respectively. The percent difference between the simulated and actual electrical energy consumption measured during winter for ventilation fan, light, and motor were 7.9%, 5.2% and 8.2%, respectively. The simulated and actual natural gas consumption had an 18.7% difference. In gestation room, the percent difference between the simulated and actual electrical energy consumption measured during summer for ventilation fan, light, and motor were 11.3%, 5.0% and 0.65%, respectively. The percent difference between the simulated and actual electrical energy consumption measured during winter for ventilation fan, light, and motor were 9.9%, 10.3% and 10.6%, respectively. There was no natural gas consumption during the monitoring period in the gestation room. In calculating the simulated gas consumption, no supplemental heat was required, thus, gas consumption was also zero.



a) Electrical energy consumption in summer

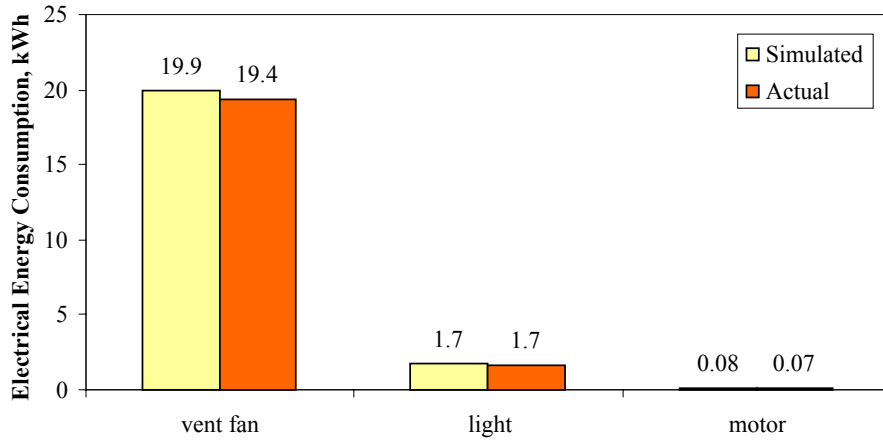


b) Electrical energy consumption in winter

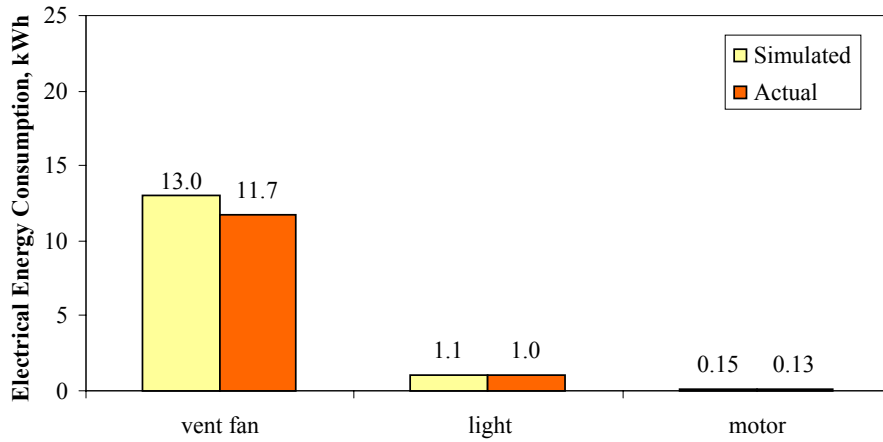


c) Natural gas consumption in winter

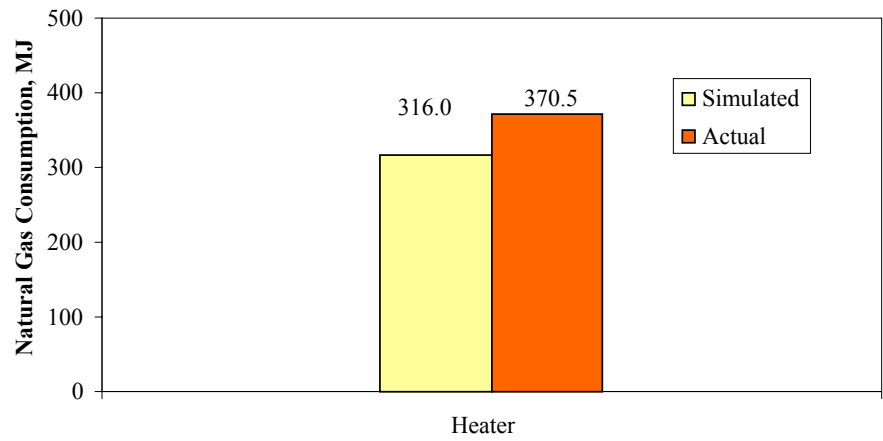
Figure 5.7 Simulated and actual energy consumption in farrowing room (Barn B)



a) Electrical energy consumption in summer

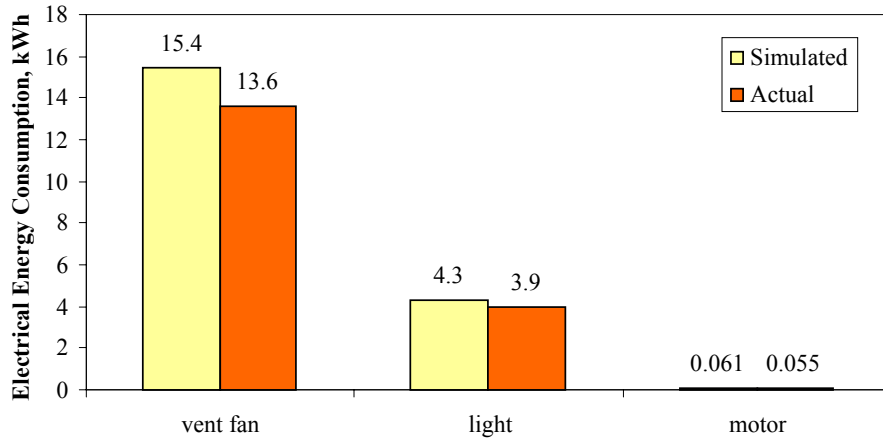


b) Electrical energy consumption in winter

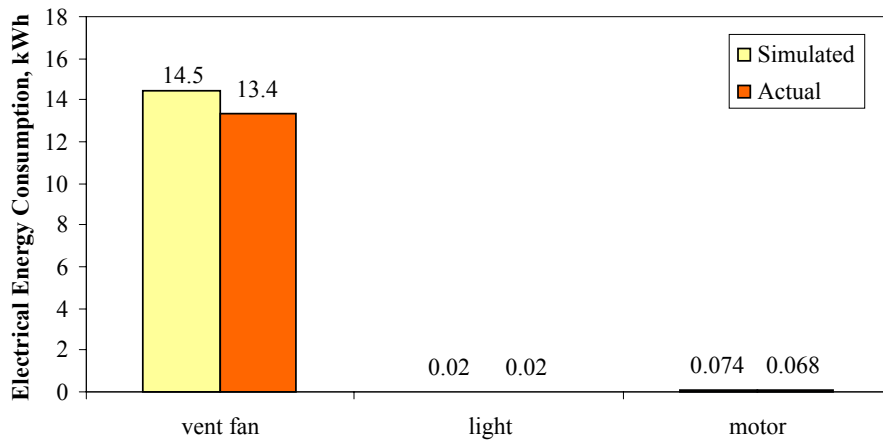


c) Natural gas consumption in winter

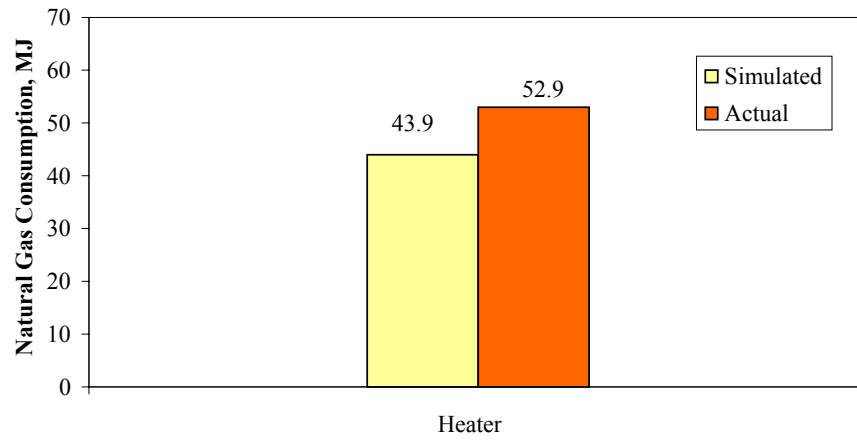
Figure 5.8 Simulated and actual energy consumption in nursery room (Barn B)



a) Electrical energy consumption in summer

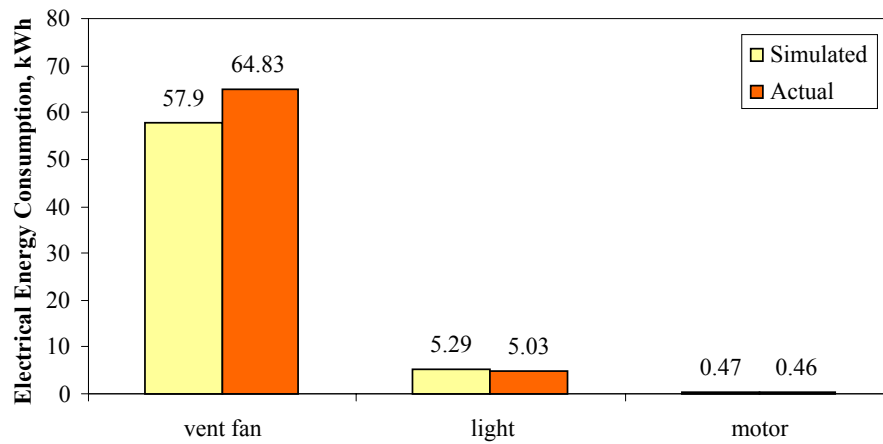


b) Electrical energy consumption in winter

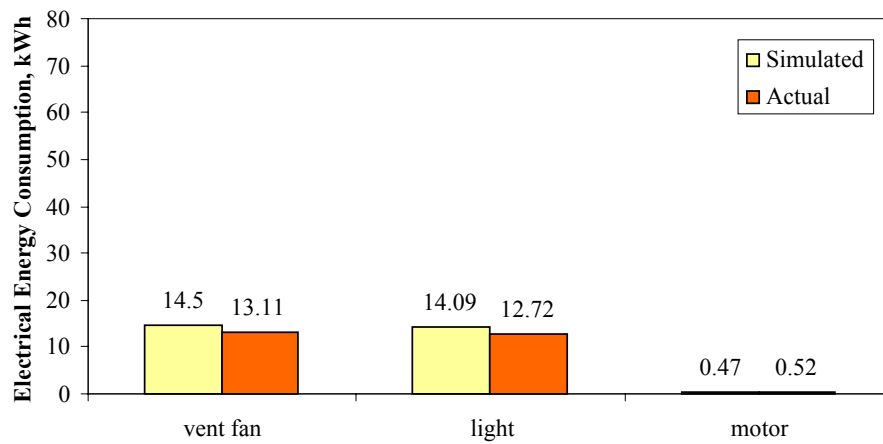


c) Natural gas consumption in winter

Figure 5.9 Simulated and actual energy consumption in grow-finish room (Barn B)



a) Electrical energy consumption in summer



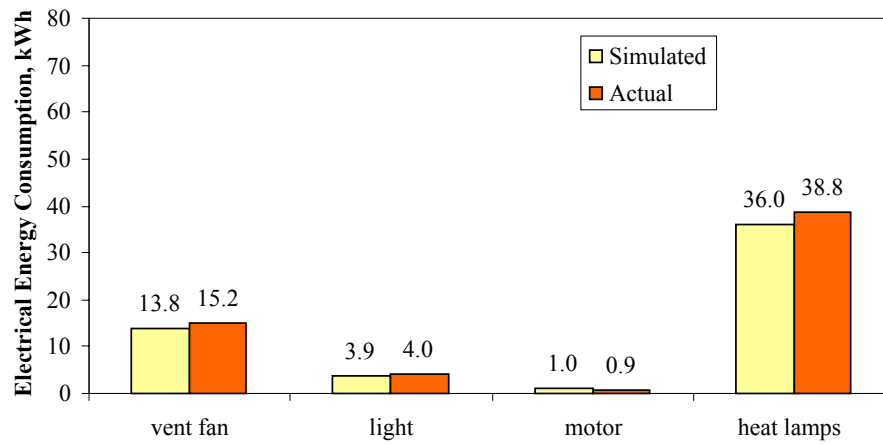
b) Electrical energy consumption in winter

Figure 5.10 Simulated and actual energy consumption in gestation room (Barn B), No gas consumption

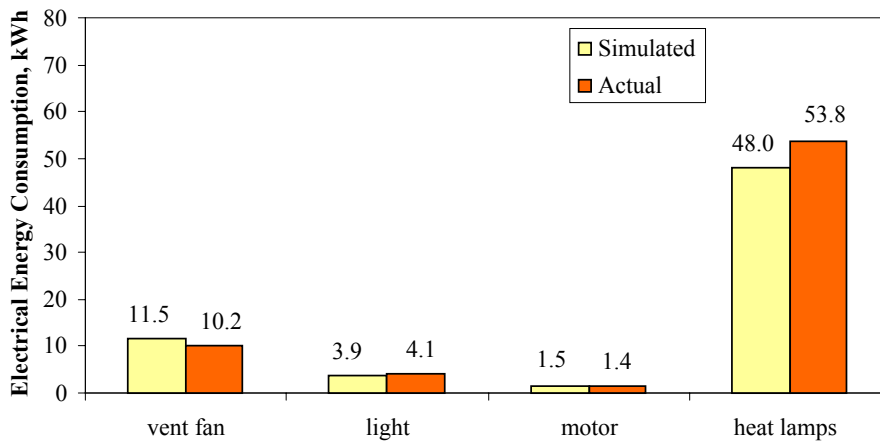
5.3.1.3 Model Validation for Barn C

The results of model validation for Barn C are shown in Figures 5.11 and 5.12. In farrowing room monitored, the percent difference between the simulated and actual electrical energy consumption measured during summer for ventilation fan, light, motor and heat lamp were 9.6%, 4.2%, 6.1% and 7.4%, respectively. The percent difference between the simulated and actual electrical energy consumption measured during winter for ventilation fan, light, motor and heat lamp were 11.4%, 5.4%, 5.5% and 11.4%, respectively. The simulated and actual propane gas consumption had a percent difference of 10.1%.

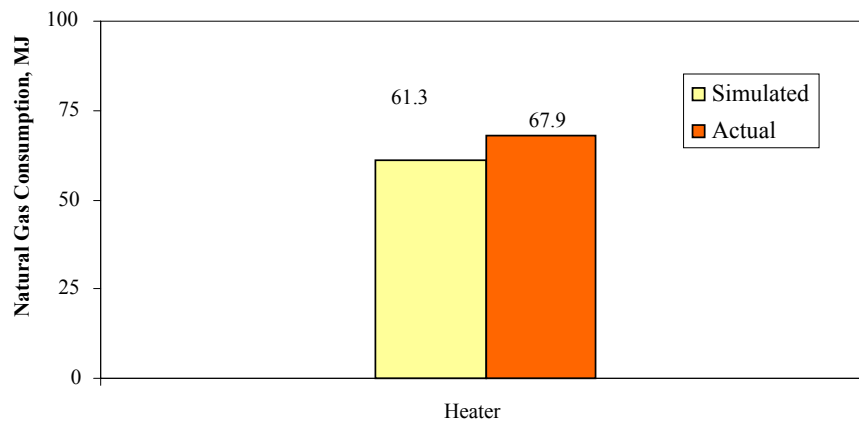
In gestation room monitored, the percent difference between the simulated and actual electrical energy consumption during summer for ventilation fan, light, motor and recirculation fan were 11.2%, 1.9%, 11.1% and 4.0%, respectively. The percent difference between the simulated and actual electrical energy consumption during winter for ventilation fan, light, motor and recirculation fan were 3.4%, 9.1%, 7.4%, and 3.6%, respectively. There was no propane gas consumption measured during the monitoring period. The simulated gas consumption was calculated using heat balance. There was no required supplemental heat computed, thus, the simulated gas consumption was also zero.



a) Electrical energy consumption in summer

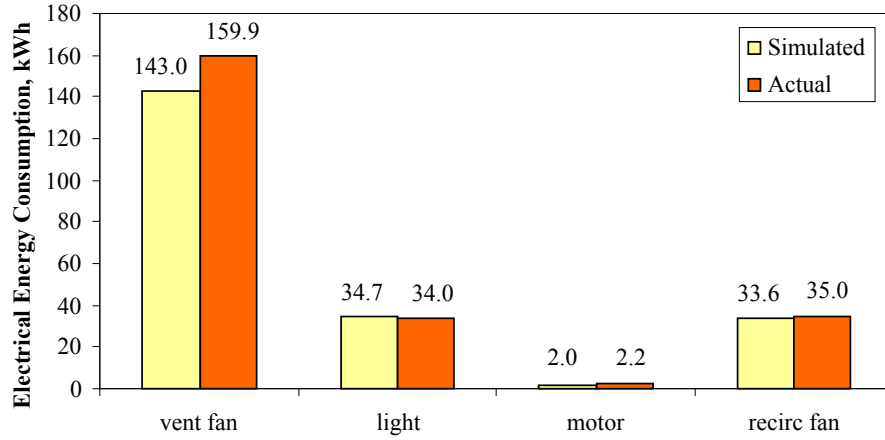


b) Electrical energy consumption in winter

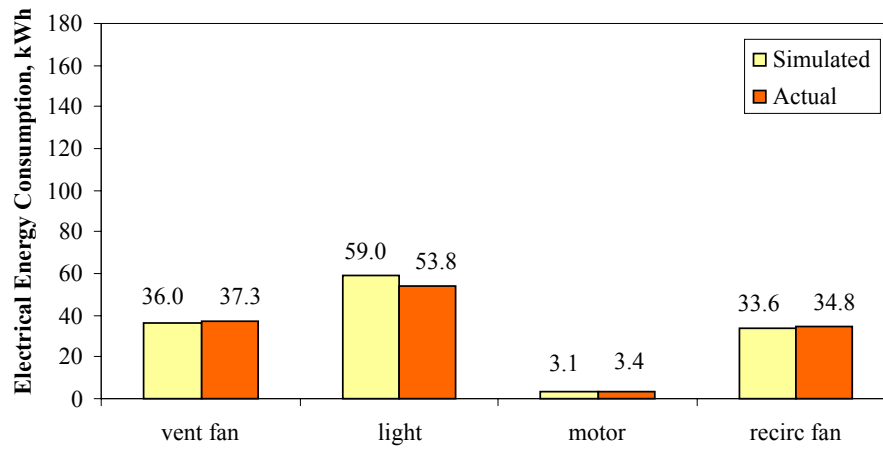


c) Propane gas consumption in winter

Figure 5.11 Simulated and actual energy consumption in farrowing room (Barn C)



a) Electrical energy consumption in summer

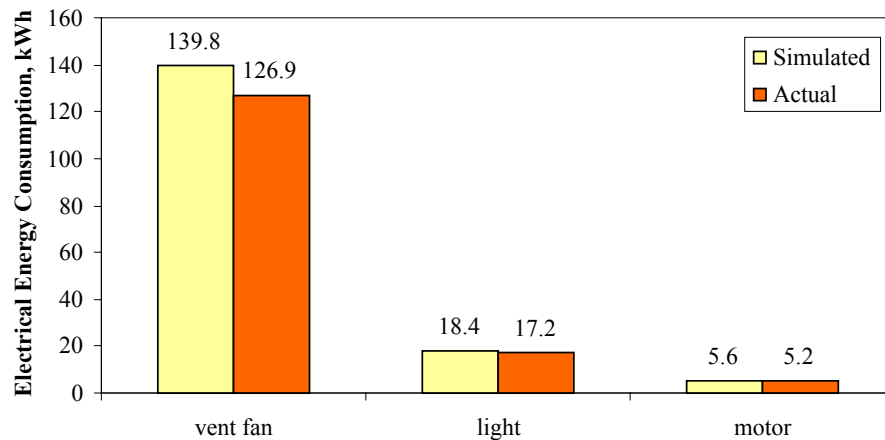


b) Electrical energy consumption in winter

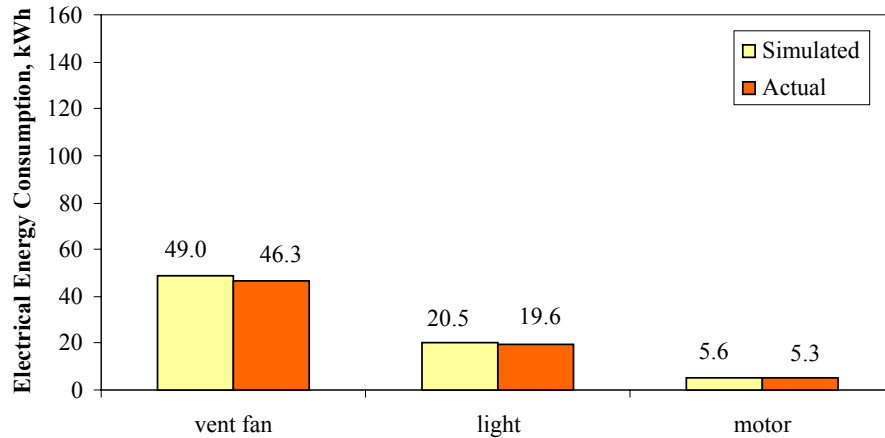
Figure 5.12 Simulated and actual energy consumption in gestation room (Barn C), No gas consumption

5.3.1.4 Model Validation for Barn D

The results of the model validation for Barn D are shown in Figures 5.13. In grow-finish room monitored, the percent difference between the simulated and actual electrical energy consumption measured during summer for ventilation fan, light, and motor were 9.7%, 6.7% and 7.3%, respectively. The percent difference between the simulated and actual electrical energy consumption measured during winter for ventilation fan, light, and motor were 5.8%, 4.7% and 5.8%, respectively. There was no natural gas consumption measured during the monitoring period. There was no required supplemental heat computed, thus, the simulated gas consumption was also zero.



a) Electrical energy consumption in summer



b) Electrical energy consumption in winter

Figure 5.13 Simulated and actual electrical energy consumption in grow-finish room (Barn D), No gas consumption

Table 5.1 shows that the simulated values and measured values were mostly within 10% difference indicating close agreement between the simulated and the measured energy consumption. These values implied that the model can be used to predict the energy consumption in the types of barn monitored with reasonable accuracy. However, the error in this case can be attributed to the accuracy of the instruments used during actual energy measurement and assumptions made in the simulation, which affects the actual readings and simulated values. The outside temperature may also contribute to the errors in the calculated energy consumption due to the proximity of weather station from each barn. The temperature difference between the nearest station and the barn can significantly affect the simulated energy consumption. The number of hours the equipment was in use can also be a source of error on the simulation part of this study because the information used in the simulation was only an estimate of the actual operation.

5.3.1.5 Verification of electrical energy consumption using ventilation graph and actual inside air temperature on model validation

The electrical energy consumption computed using the ventilation graph and that using the actual inside air temperature were discussed in Appendix H. A sample calculation was also shown to illustrate how the values were obtained.

The electrical energy consumption computed using the ventilation graph was 15.6 kWh, 19.6 kWh, 63.8 kWh and 117.8 kWh for farrowing, nursery, grow-finish and gestation rooms in barn A, respectively. The actual energy consumption using the actual inside air temperature was 16.6 kWh, 22 kWh, 63.8 kWh and 116 kWh for farrowing, nursery, grow-finish and gestation rooms in barn A, respectively. The percent difference ranged from 2 to 12 % (averaged of 5%). Thus, the ventilation graph can be used with reasonable accuracy in the calculation of the simulated annual energy consumption.

Table 5.1 Simulated and measured electrical and gas consumption of different equipment

Equipment	Simulated Value, kWh	Measured Value, kWh	Percent Difference, %
1. Exhaust Fans			
Barn A	34.46	35.36	-2.57
Barn B	20.05	19.91	0.72
Barn C	51.09	55.66	-8.57
Barn D	94.44	86.57	8.70
Average (SD)			5.14 (4.11)
2. Recirculation Fans			
Barn A	9.90	9.15	7.81
Barn B (No data)			
Barn C	33.60	34.91	-3.84
Barn D (No data)			
Average (SD)			5.82 (2.81)
3. Lights			
Barn A	13.17	12.84	2.50
Barn B	4.33	4.03	7.19
Barn C	25.33	23.98	5.49
Barn D	19.44	18.37	5.63
Average (SD)			5.20 (1.96)
4. Feed Motors			
Barn A	1.06	1.02	4.19
Barn B	0.18	0.18	-0.49
Barn C	1.89	1.97	-4.33
Barn D	5.60	5.24	6.53
Average (SD)			3.88 (2.50)
5. Heater Fan			
Barn A	11.67	11.06	5.43
Barn B			
Barn C	9.50	9.41	1.03
Barn D			
Average (SD)			3.23 (3.11)
6. Heat pad			
Barn A	16.22	17.16	-5.63
Barn B	13.80	13.59	1.53
Barn C (No heat pad)			
Barn D (No heat pad)			
Average (SD)			3.58 (2.90)
7. Heat lamp			
Barn A	33.08	33.01	0.21
Barn B	4.50	4.14	8.40
Barn C	42.00	46.28	-9.69
Barn D (No heat lamp)			
Average (SD)			6.10 (5.14)
8. Gas Consumption, MJ			
Barn A	17.12	18.39	-7.15
Barn B	6.67	7.62	-13.35
Barn C	2.43	2.20	10.11
Barn D			
Average (SD)			10.20 (3.10)

Note: Simulated and measured values are the average of summer and winter values for all rooms monitored.

5.3.2 Evaluation of Energy Conservation Strategies to Baseline Case

5.3.2.1 Lighting

Using equation 5.18, the electrical energy consumption of different lighting systems was computed. The total luminous flux in each room monitored using the existing T-12 lamps were 43,656 lumen for farrowing and nursery; 52,387 lumens for grow-finish; and 209,549 lumens for gestation rooms as shown in Appendix I. These light were used in assessing other lighting systems and in determining how many lamps can provide the same luminous flux.

The lights used in barn A were 34-W T-12 fluorescent lamps. There were 10 fixtures (2 lamps per fixture) for farrowing and nursery rooms while 12 and 48 fixtures for grow-finish and gestations rooms, respectively, and were considered as the baseline case. One T-12 lamp provided 64.2 lumens per Watt as per manufacturer's specification. The electrical energy consumption per day per room monitored was then computed and the results are shown in Table 5.2.

The first lighting option was 32-W T-8 fluorescent lamps. This lower wattage but higher lumen T-8 lamp can provide 81 lumens per Watt. This implied that the same luminous flux can be provided by fewer 32-W T-8 lamps. The baseline 10 fixtures of 34-W T12 lamps for farrowing and nursery rooms can be reduced to 9 fixtures. For grow-finish and gestation rooms, 12 and 48 fixtures can be reduced to 10 and 41 fixtures. This can save 18, 221 kWh per year (30 kWh/sow) for entire production area of barn A.

The second lighting option was 25-W T-8 fluorescent lamps. This lower wattage but higher lumen T-8 lamp can provide 91 lumens per Watt. This implied that the same luminous flux can be provided by fewer 32-W T-8 lamps. Because of its lower wattage, it can give an annual savings of 26,718 kWh (44 kWh/sow) for entire production area of barn A.

The third lighting option was 28-W T-5 lamps. This lower wattage but higher lumen T-5 lamp can provide 104 lumens per Watt. This implied that the same luminous flux can be provided by

fewer 28-W T-5 lamps. The baseline 10 fixtures of 34-W T12 lamps for farrowing and nursery rooms can be reduced to 8 fixtures. For grow-finish and gestation rooms, 12 and 48 fixtures can be reduced to 9 and 36 fixtures, respectively. This can save 35, 974 kWh per year (60 kWh/sow) for entire production area of barn A.

The fourth lighting option was 24-W T-5 HO lamps. This lower wattage but higher lumen T-5 lamp can provide 86 lumens per Watt. This implied that the same luminous flux can be provided by fewer 24-W T-5 lamps. The baseline 10 fixtures of 34-W T12 lamps for farrowing and nursery rooms can be reduced to 9 fixtures. For grow-finish and gestation rooms, 12 and 48 fixtures can be reduced to 11 and 45 fixtures, respectively. This can save 22,916 kWh per year (38 kWh/sow) for entire production area of barn A. Details on the different types of lights, light intensity, and number of fixtures and sample calculation are shown in Appendix I.

Table 5.3 shows the payback period for replacing T-12 lamps with energy efficient lights. By replacing T-12 lamps by T-8 lamps, the payback period was 0.6 years (32 W lamp) and 0.7 years (25 W). The total savings per year for 32 W T-8 lamps was \$1709 and \$2,506 for 25 W T-8 lamps. By replacing T-12 lamps with T-5 lamps, the payback period was 3 years for 28 W T-5 and 8.2 years for 24 W T-5 high output lamps. It will take longer to recoup the investment for T-5 high output lamps because of its high installation cost and capital cost.

In the financial analysis of the four options, the cost computation included the installation cost (i.e. materials and labor). The cost of ballast and fixtures were considered for replacing T12 lamps with T5 lamps. No ballast or fixture required in switching from T12 lamps to T8 lamps.

Table 5.2 Annual electrical energy consumption and annual savings from using energy efficient lighting in Barn A

Type of Lights	Farrowing		Nursery		Grow-Finish		Gestation		Total kWh /yr for entire production area	Savings from replacing T12 lamps, kWh/yr	Savings from replacing T12 lamps, \$/yr (@ \$0.0938 per kWh (Saskpower))
	kWh per day per room	kWh per year for 8 rooms*	kWh per day per room	kWh per year for 8 rooms*	kWh per day per room	kWh per year for 14 rooms*	kWh per day per room	kWh per year for 2 rooms*			
1. Baseline design (F34T12) 34 W T-12 fluorescent	5.4	15,768	5.4	15,768	6.5	33,215	45.7	33,361	98,112		BASELINE
2. Option 1: (F32T8) 32 W T-8 fluorescent	4.6	13,455	4.6	13,455	5.1	26,163	36.7	26,817	79,891	18,221	\$1,709.11
3. Option 2: (F25T8) 25 W T-8 fluorescent	4.0	11,680	4.0	11,680	4.8	24,528	32.2	23,506	71,394	26,718	\$2,506.15
4. Option 3: (F28T5) 28 W T-5 fluorescent	3.6	10,465	3.6	10,465	4.0	20,604	28.2	20,604	62,138	35,974	\$3,374.40
5. Option 4: (F24T5HO) 24 W T-5 high output	4.2	12,334	4.2	12,334	5.0	25,509	34.3	25,019	75,196	22,916	\$2,149.54

* The total energy consumption per stage of production is computed based on the number of rooms and number of days in a year (365 days).

Table 5.3 Financial analysis on using energy efficient lighting in Barn A

Lighting options	Farrowing	Nursery	Grow-Finish	Gestation	WHOLE BARN
1. Baseline design (F34T12) 34 W T-12 fluorescent lamp					
# of fixtures	10	10	12	48	
Cost of lamp, Cdn\$/lamp (\$5.22/lamp)	\$105.77	\$105.77	\$126.92	\$507.68	
TOTAL COST	\$505.77	\$505.77	\$606.92	\$2,427.68	
2. Option 1: (F32T8) – 32 W T-8 fluorescent lamp					
# of fixtures	9	9	10	41	
Cost of lamp, Cdn\$/lamp (\$7.25/lamp)	\$132.21	\$132.21	\$146.90	\$602.29	
TOTAL COST	\$132.21	\$132.21	\$146.90	\$602.29	\$1,013.61
TOTAL SAVINGS per year compared to baseline design					\$1,709.11
payback period					0.6
3. Option 2: (F25T8) – 25 W T-8 fluorescent lamp					
# of fixtures	10	10	12	46	
Cost of lamp, Cdn\$/lamp (\$10.90/lamp)	\$220.86	\$220.86	\$265.03	\$1,015.94	
TOTAL COST	\$220.86	\$220.86	\$265.03	\$1,015.94	\$1,722.68
TOTAL SAVINGS per year compared to baseline design					\$2,506.15
payback period					0.7
4. Option 3: (F28T5) – 28 W T-5					
# of fixtures	8	8	9	36	
Installation cost, Cdn\$/fixture	\$320.00	\$320.00	\$360.00	\$1,440.00	
Cost of lamp, Cdn\$/lamp (\$48.75/lamp)	\$790.22	\$790.22	\$889.00	\$3,555.98	
Ballast and fixture cost (\$28.99)	\$231.92	\$231.92	\$260.91	\$1,043.64	
TOTAL COST	\$1,342.14	\$1,342.14	\$1,509.91	\$6,039.62	\$10,233.80
TOTAL SAVINGS per year compared to baseline design					\$3,374.40
payback period					3.0
5. Option 4: (F24T5HO) – 24 W T-5 high output					
# of fixtures	12	12	14	52	
Installation cost, Cdn\$/fixture	\$480.00	\$480.00	\$560.00	\$2,080.00	
Cost of lamp, Cdn\$/lamp (\$60.00/lamp)	\$1,458.86	\$1,458.86	\$1,702.01	\$6,321.74	
Ballast and fixture cost (\$34.99)	\$419.88	\$419.88	\$489.86	\$1,819.48	
TOTAL COST	\$2,358.74	\$2,358.74	\$2,751.87	\$10,221.22	\$17,690.58
TOTAL SAVINGS per year compared to baseline design					\$2,149.54
payback period					8.2

Note: The cost of lamp was obtained from Philips electronic catalogue 2008 (<http://www.prismaecat.lighting.philips.com>). Cost of installation, ballast and fixtures were obtained from <http://www.naturallighting.com>.

5.3.2.2 Creep Heating

The baseline case on creep heating for farrowing room in barn A was 169-W heat pad in combination with 175-W heat lamp. Heat lamps were operated for 3 days and heat pads were used continuously for 2 weeks. Lactation period was 2 weeks after which the piglets were transferred to nursery room and the sows were transferred back to gestation room. There was approximately 24 farrowing times per room in one year. The required temperature range for newborn pigs is 32°C to 35°C. MacDonald, et al. (2000) conducted research comparing heat pads and heat lamps and its effect on animal performance. No significant difference was observed on animal performance between the two types of creep heating systems. Thus, it was considered in this study to completely replace existing combination of heat lamp and heat pad by using heat pads only as part of the energy saving strategy.

Table 5.4 shows the baseline case for Barn A. Heat lamps and heat pads in barn A consumed 121,774 kWh per year. The electrical energy consumed was computed using equations 5.19 and 5.20. In the same table, three energy conservation strategies were applied. The first strategy was the use of a lower wattage heat lamp (100 W) and lower wattage heat pad (120 W or 60 W per crate). The same schedule of operation was applied to this conservation strategy. By replacing the 175-W heat lamp and 169-W heat pad, savings of 40,673 kWh per year (\$3,815/yr) can be attained. The second strategy was the use of 169-W heat pads only which resulted to a savings of 38,707 kWh per year (\$3,630/yr). The third strategy was the use of 120-W heat pad which can reduce the energy consumption per year by 62,792 kWh (\$5,889). Furthermore, the lower wattage heat lamps (100 W) and heat pads (120 W) can provide the a lower temperature range but still within the required 32°C to 35°C. Higher wattage (175-W heat lamp and 169-W heat pad) can go as high as 40°C (MacDonald et al., 2000). Table 5.4 also shows that the cost of replacing the existing heat pads and heat lamps for a lower wattage is \$7,573 while there is no cost associated with eliminating the use of heat lamps and just using the existing heat pad. On the other hand, eliminating the use of heat lamp and use of a lower wattage heat pad (120 W) can cost \$6,652 for electrical energy consumption. The payback period for replacing the existing heat lamps and heat pads by lower wattage is 2 years while the payback period for replacing the existing creep heating system by using 120-W heat pad alone is 1.1 year.

Table 5.4 Annual electrical energy consumption and annual savings on using energy efficient creep heating system in Barn A

Creep Heating System	kWh per day per room	kWh per year for 8 farrowing rooms	Savings, kWh/yr	\$/yr savings* @ \$0.0938 per kWh (Saskpower)	Cost of replacement**
1. Baseline Design - Combination of heat lamp 175 W and heat pad 169 W					
a. Heat lamps, kWh (3 days per farrowing)	67.2	38,707	Baseline design		
b. Heat pads, kWh (24-h continuous operation for 2 weeks per farrowing)	32.4	83,067			
TOTAL		121,774			
2. Option 1: Combination of heat lamp 100 W and heat pad 120W double pad					
a. Heat lamps, kWh (3 days per farrowing)	38.4	22,118	40,673	\$3,815.15	\$7,573.12
b. Heat pads, kWh (24-h continuous operation for 2 weeks per farrowing)	23.0	58,982			
TOTAL		81,101			
3. Option 2: Heat pads 169 W (24-h continuous operation for 2 weeks per farrowing)					
TOTAL	32.4	83,067	38,707	\$3,630.74	-
4. Option 3: Heat pad 120 W (24-h continuous operation for 2 weeks per farrowing)					
TOTAL	23.0	58,982	62,792	\$5,889.86	\$6,652.80

Note: Farrowing period in Barn A was 2 weeks. Farrowing times was approximately 24 times per room per year.

* Savings were computed based on the difference of the conservation strategy and the baseline design.

** Cost of replacement was based on the price of the heat lamps and pads (\$7.19 for 100-W heat lamp, \$8.25 for 175-W heat lamp, \$ 103.95 for 120-W heat pad and \$124.95 for 169-W heat pad). Information on price of heat lamps (model: Broan Kenmore) and heat pads (model: Stanfield) were obtained from <http://www.nextag.com> (2008) and <http://www.enasco.com> (2008).

5.3.2.3 Recirculation Fan

Table 5.5 shows the baseline case of recirculation fan with an efficiency of 7.5 cfm/W for farrowing and nursery and 9.5 cfm/W for grow-finish and gestation rooms. Using recirculation fan with higher cfm/W rating of 8 cfm/W rating for farrowing and nursery rooms and 11 cfm/W rating for grow-finish and gestation rooms, savings of 9,872 kWh per year can be attained.

There were 2 recirculation fans in farrowing and nursery rooms, 3 fans in gestation room and 1 fan in grow-finish room. The recirculation fan capacity in farrowing room was the same as that in nursery room, while the recirculation fan in gestation room was the same as that in grow-finish room. The total cost of replacing the existing recirculation fans with energy efficient fans was \$30,716.28 and the savings of \$925.95 per year was expected. The payback period for this strategy was more than 10 years due to high cost of replacement and relatively small savings per year. Additional installation cost may result to a longer payback period.

5.3.2.4 Exhaust Fan

The electrical energy consumption of exhaust fans was determined using equations 5.23 and 5.24. The ventilation graph developed for each room was used to determine the ventilation rate at a given outdoor temperature. Annual weather data shown in Appendix F was used as the outdoor temperature.

Table 5.6 shows the baseline case and the applied conservation strategy for exhaust fans. The strategy used in this part was increasing the cfm/W rating of exhaust fan based on commercially available energy-efficient fans.

In order to determine the energy consumption of exhaust fans with higher cfm/W rating, the model implemented through a spreadsheet was used. By increasing the cfm/W rating of the exhaust fans, significant reduction in the energy cost can be achieved. Table 5.6 shows the annual savings for the entire production area.

There were 2 exhaust fans in farrowing room, 3 fans in nursery room, 5 fans in grow-finish, and 8 fans in gestation room. In farrowing room, the existing stage 1 and 2 fans have efficiencies of 7.5 and 10 cfm/W, respectively. The applied conservation strategy was replacing the existing fans with commercially available fan models with the same capacity but higher efficiencies of 9.50 and 12 cfm/W, respectively. In nursery room, the existing stage 1 has efficiency of 6.5 cfm/W while stages 2 and 3 fans have efficiency 10 cfm/W. The applied conservation strategy was replacing the same fan capacity with commercially available fans that have higher efficiencies of 10 and 12 cfm/W, respectively. In grow-finish room, the existing stages 1 and 2 have efficiency of 10 cfm/W while stages 3 and 4 fans have efficiency 11.4 cfm/W. The applied conservation strategy was replacing the same fan capacity with commercially available fans that have higher efficiencies of 12 and 13 cfm/W, respectively. In gestation room, the existing stage 1 has efficiency of 7.5 cfm/W; stage 2 has efficiency of 11 cfm/W while stages 3 and 4 fans have efficiency 14.8 cfm/W. The applied conservation strategy was replacing the same fan capacity with commercially available fans that have higher efficiencies of 9.5, 13 and 16 cfm/W, respectively.

The total cost of replacing the existing exhaust fans with energy efficient fans was \$19,147.94 while savings of \$11,151.91 per year can be attained. The payback period for this strategy was 1.7 years, assuming no change in fan efficiency throughout the period. Additional installation cost may result to a longer payback period.

Table 5.5 Annual electrical energy consumption and annual savings from using energy efficient recirculation fan in Barn A

Recirculation fan	Farrowing		Nursery		Grow-Finish		Gestation		Total kWh per year for entire production area	Savings from existing recirculation fans, kWh/yr	Savings from increasing cfm/w, \$/yr @ \$0.0938 per kWh (Saskpower)
	kWh per day per room	kWh per year for 8 room*	kWh per day per room	kWh per year for 8 room*	kWh per day per room	kWh per year for 14 rooms*	kWh per day per room	kWh per year for 2 rooms*			
1. Baseline Case : Fan With 7.5 cfm/W	3.84	11,213	3.84	11,213	8.51	43,479	25.53	18,634	84,539		BASELINE
2. Option 1: Fan With 8 cfm/W	3.60	10,512	3.6	10,512	7.35	37,550	22.05	16,093	74,667	9,872	\$925.95

Note: The recirculation fans run continuously for the entire year.

116

Table 5.6 Annual electrical energy consumption and annual savings on using energy efficient exhaust fan in Barn A

Exhaust Fans	Farrowing	Nursery	Grow-Finish	Gestation	Total kWh per year for entire production area	Savings, kWh per year	\$/yr (@ \$0.0938 per kWh (Saskpower))
	kWh per year for 8 rooms	kWh per year for 8 rooms	kWh per year for 14 rooms	kWh per year for 2 rooms			
1. Baseline Design - Exhaust Fans							
TOTAL	37,135.1	50,975.0	285,699.3	61,514.2	435,323.6		Baseline
2. Option 1: Energy Efficient Exhaust Fans							
TOTAL	30,153.0	41,938.0	201,809.0	42,534.0	316,434.0	118,889.6	\$11,151.85

Note: Additional installation cost may result to a longer payback period.

5.3.2.5 Feed Motor

The feed motor for nursery, grow-finish, and gestation rooms had power rating of 0.5 hp with 70% efficiency. A higher efficiency motor with lower rating can be used to provide the same power. NEMA recommended 78-82% motor efficiency for 1 hp motor. The strategy applied was to use the same size of motor (0.5 hp) with a higher efficiency of 82%. Table 5.7 shows the annual energy consumed by feed motors of 1,524 kWh which was computed using equation 5.21. An annual energy savings of 261.4 kWh can be attained if the existing motor was replaced by a higher efficiency motor. The cost of replacing the motor with higher efficiency motor was \$12,052.00 (Baldor motor at \$262.00 each). The investment for this strategy had a longer payback period (70 years) as the feed motors were used intermittently and for a short period of approximately 1 to 4 hours per day (365 hours to 1460 hours per year). Thus, it appears that this strategy was not a sound option. However, the result of the simulation on feed motors can be used for new barn construction. Potential savings of \$173.17/yr can be achieved by choosing higher efficiency motors. Additional installation cost may result to a longer payback period.

Table 5.7 Annual electrical energy consumption and annual savings from using higher efficiency feed motor in Barn A

Feed motor	Nursery	Grow-Finish	Gestation	Whole barn	Savings per year, kWh	\$/yr (@ \$0.0938 per kWh (Saskpower))
1. Baseline design: Feed motor (0.5 hp @70% efficiency)						
# of motors	8	28	10			
Hours of use per day						
summer	3	1	1			
winter	4	4	2			
Total power available*	2.1	7.3	2.6			
Total Annual energy consumption, kWh**	2,668.4	6,671.1	1,429.5	10,769.1		Baseline
2. Option 1: Feed motor (0.5 hp @ 82% efficiency)						
HP	0.50	0.50	0.50			
motor efficiency	0.82	0.82	0.82			
# of motors	1	2	5			
Hours of use per day						
summer	3	1	1			
winter	4	4	2			
Total power available*	2.4	8.6	3.1			
Total Annual energy consumption, kWh**	3,125.9	7,814.7	1,674.6	12,615.2	1,846.1	\$173.17

* Total power available was computed by multiplying the quantity of motor, its hp rating, and its efficiency.

** Annual energy consumption was based on 365 days per year and average operating hours in winter and summer.

5.3.2.6 Heat Recovery

Space heating represents a significant input cost for swine operations in cold climate (Barber and Ford, 1989). A cross-flow type air-to-air heat exchanger was used to determine how much heat can be recovered from heat lost through exhaust air and to quantify the savings associated with it. During normal operation, exhaust fan draws stale barn air into the exhaust passages of the core, and forces it outside through a nozzle. The supply fan draws fresh outside air into the supply passages of the core and forces it through a nozzle into the barn. The stale exhaust air does not mix with the fresh supply air in the core as shown in Figures 5.14.

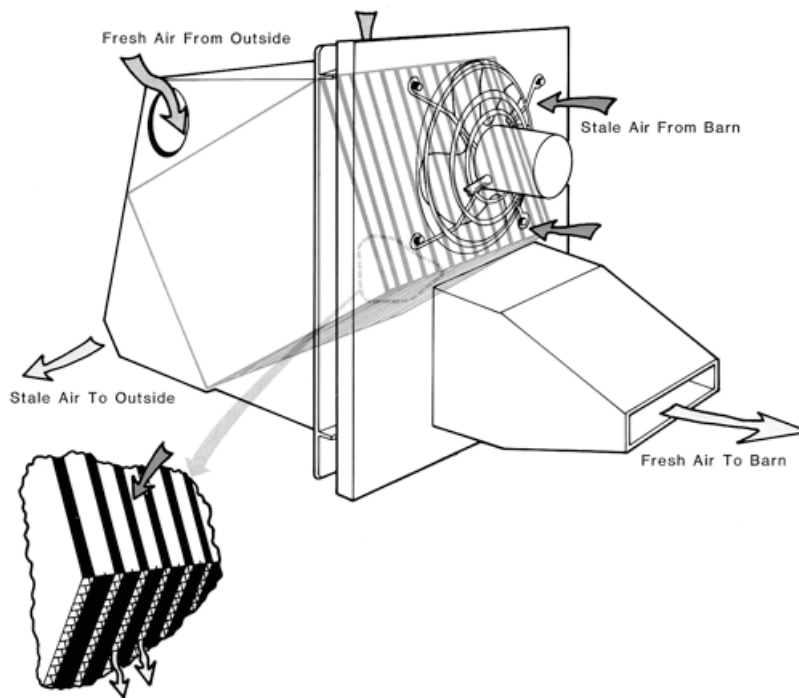


Figure 5.14 Cross-flow heat exchanger (Source: Del-Air)

As shown in Figure 5.15, the air coming out from the barn with temperature t_b is the major contributor to heat loss in barns during winter. The heat loss from exhausted air becomes the heat gain of the supply air in the heat exchanger. The following equation (ASHRAE, 2005) can be used to determine the temperature of the incoming air (after heat exchange).

$$t_i = t_o + \varepsilon (t_b - t_o) \quad (5.26)$$

where:

t_i is the temperature of incoming air after heat exchange, °C

t_o is the temperature of outdoor air, °C

t_b is the temperature of exhausted air before heat exchanger, °C

ε is the effectiveness of heat exchanger, decimal (specified by the manufacturer)

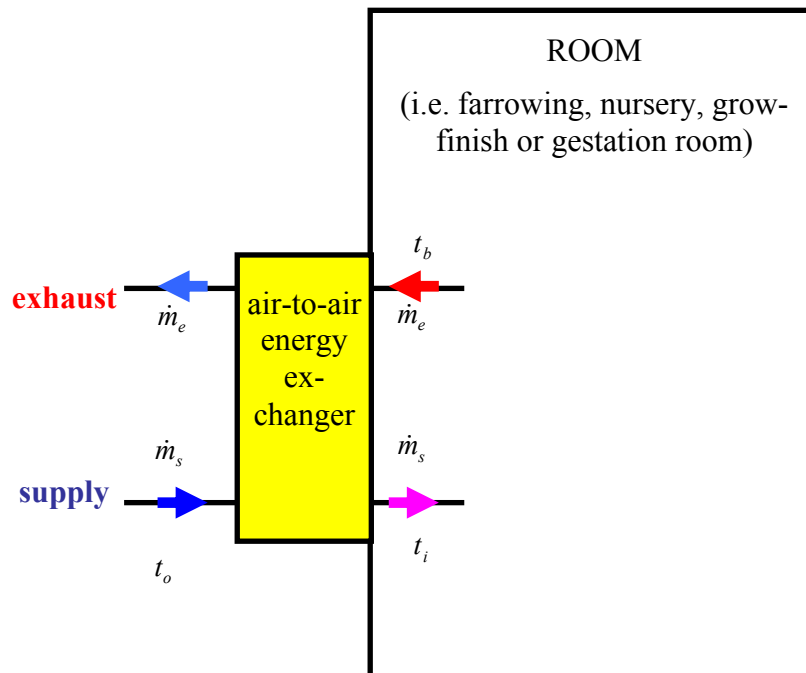


Figure 5.15 Heat exchange between exhaust and supply air

The heat recovered from the exhaust air can be computed using the following equation. The mass flow rate can be determined by multiplying the air density and the ventilation rate.

$$q_{recovered} = m c_p (t_i - t_o) \quad (5.27)$$

where:

m is the mass flow rate of the air, kg/s

C_p is the specific heat of air, KJ/kg-K

t_i is the temperature of incoming air after heat exchange, K

t_o is the temperature of outside air before heat exchange, K

The simulated values for natural gas consumed by space heater for farrowing, nursery, grow-finish and gestation are 15,541 m³/yr; 48,233 m³/yr; 10,270 m³/yr and 908 m³/yr; respectively. The simulated values were computed based on the hourly average 5-yr weather data and shown in Figure 5.16. The 5-year weather data on an hourly average is shown in Appendix F.

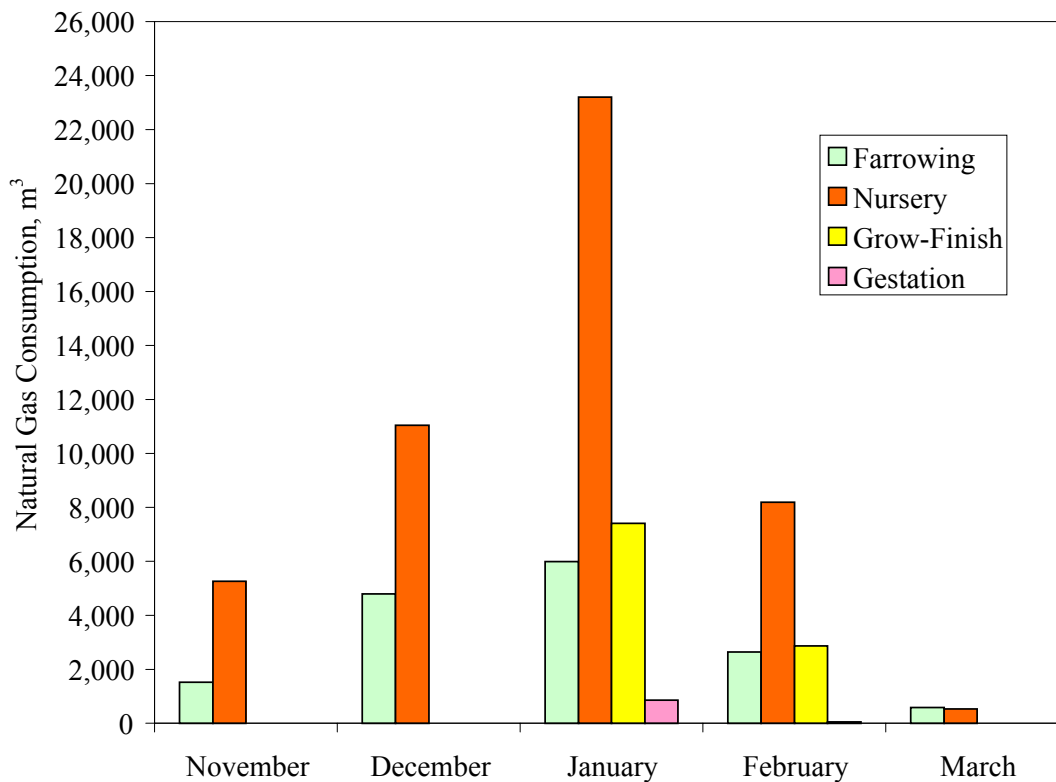


Figure 5.16 Simulated monthly natural gas consumption for different production areas (Barn A)

Using the cross-flow heat exchanger with effectiveness of 0.7 (specified by manufacturer), the heat recovered for farrowing, nursery, grow-finish, and gestation (assuming complete air mixture inside the barn) can maintain the set-point temperature in the room without requiring space heater operation. From November to March (with hourly average of 5-year temperature data), no supplemental heat was required in each room monitored based on the computed values. The maximum average outside temperature data used for this period was -23.3°C . This means that an annual saving of $74,952\text{ m}^3$ can be attained due to less gas consumed for space heating. At $\$0.3272/\text{m}^3$ (SaskEnergy, 2007), a total of $\$24,524$ can be saved per year for Barn A. The estimated cost of installing heat exchanger as part of the fan operation which would provide the minimum ventilation was $\$21,346$ and can be recouped in less than 1 year. The cost was estimated based on the number of heat exchanger that should be installed to meet the minimum ventilation for each room. The number of heat exchanger depends on the minimum ventilation rate setting in the barn. In this case, one heat exchanger should be installed in farrowing and nursery room, while 2 heat exchangers in grow-finish room and 4 exchangers in gestation room. All heat exchangers have the same capacity of 1,000 cfm (model: Del-Air RA-1000).

The savings greatly depend on the effectiveness of heat exchanger. The commercially available heat exchangers have effectiveness ranging from 0.45 to 0.70. A sensitivity analysis was done and for all rooms at 0.6 and 0.7 effectiveness of heat exchanger, no supplemental heat was required. The heat recovered and the heat generated by pigs and other sources were enough to maintain the set-point temperature for rooms at different production stages. Using heat exchanger with 0.45 effectiveness, there was no supplemental heat required for farrowing, grow-finish, and gestation. For nursery room, the supplemental heat was only required from December to February. Details on the sensitivity analysis are shown in Appendix J. Maintenance cost for heat exchanger was not accounted in the cost calculation because there was an automatic defrost cycle for the model evaluated. Some models may require additional cost for maintenance and operation (i.e. defrosting). Also, installation cost was not considered, thus a longer payback period may be expected.

5.3.2.7 Propane-gas fired radiant heater

In this strategy, instead of the existing forced-air convection heater, supplemental heat was added to the swine room environment by gas-fired radiant heater through radiation heat transfer. Radiation heat transfer occurs when energy leaves one body that has higher temperature and intercepted by another that has lower temperature (Albright, 1990). The advantage of using radiant heaters over forced-air convection heaters is the efficiency in dissipating heat. Radiant heaters heat the objects such as floor and pigs rather than the air. This gives immediate heat transfer to where it is really needed (in this case, at the animal level) unlike forced-air heater that heats the air resulting to longer heater operation and high gas consumption. Using the heating value of propane gas, the gas consumed by a radiant heater was then computed for each month and shown in Figure 5.17. The total annual gas consumption of this type of heater was 9,351 m³ (\$4,405). A savings of 65,602 m³ (\$17, 245) can be attained from using this type of heater. The Re-Verber-Ray gas-fired heater (manufactured by Detroit Radiant Products Company) was tested and compared with forced-air heater (MacDonald, 2004). The results showed that the reduction in fuel consumption was 23%. The simulated values were computed based on the outside temperature shown in Appendix F.

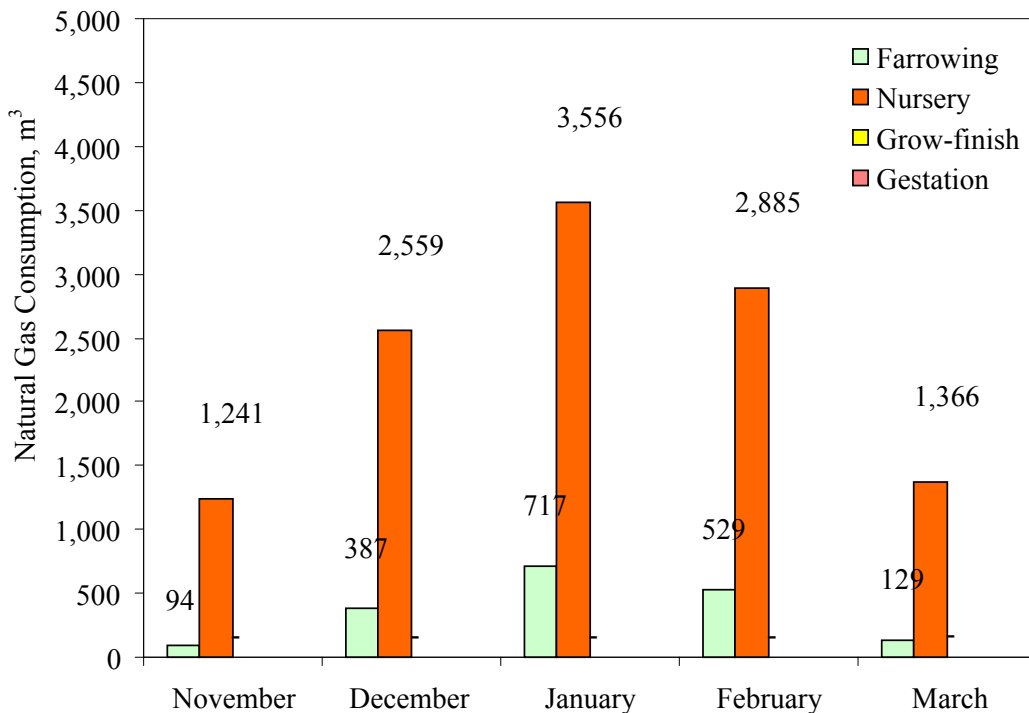


Figure 5.17 Simulated monthly gas consumption for different production areas (radiant heater)

5.4 Summary

The model developed in this part of the study was based on the basic principles of heat transfer and thermodynamics. Heat gain and heat losses were computed to determine the required ventilation to maintain the set-point temperature of a production room. The energy consumption for fans and heaters was computed and compared to the actual measured value during energy audit for validation. The validation of the model was done for four barns and using both winter and summer conditions. Percent difference was computed to determine the agreement between simulated and actual measured values of energy consumption. In most cases, a 10% percent difference or less was observed. The difference can be attributed to the accuracy of the measuring instruments used and the assumptions made in the development of the simulation model. After validating the model, a baseline case was simulated to determine the energy consumption in a barn for the entire year. In this case, all equipment was running on the specified time during normal operation. Different energy conservation strategies were then applied to the baseline case.

Energy saving from lighting can be achieved by using a lower-wattage, higher lumen lamps such as T8 and T5. By replacing the T12 fluorescent lamps with these energy efficient lamps, the number of fixtures required was fewer and the energy cost was lower. By using T8 lamps, a reduction of \$2,000/yr on energy cost can be achieved. On the other hand, T5 lamps can reduce the energy cost by an average of \$2,500/yr but will require additional costs to replace ballasts and fixtures.

Creep heating has high percentage of contribution to energy consumption in farrowing rooms. Heat lamps and heat pads were commonly used as source of supplemental heat for piglets. Lower wattage heat lamp and heat pads can be used to save energy. Replacing the 175-W heat lamp with 100-W lamp and replacing the 169-W heat pad with 120-W heat pad, annual savings of 40,673 kWh (68 kWh/sow) can be attained. By using only heat pad to supplement the required heat by piglets, annual savings ranging from 38,707 kWh or 65 kWh/sow (using 169-W heat pad) to 62,792 kWh or 105 kWh/sow (using 120-W heat pad) can be attained.

Recirculation fan runs throughout the year at a constant rate. A higher cfm/W rating of fans can reduce the electrical energy consumed. By choosing a fan with 8 cfm/W rating, annual savings of 9,800 kWh (16 kWh/sow) or \$1000 (\$1.70/sow) can be attained. Exhaust fans with higher cfm/W rating was used to evaluate the energy savings. By replacing the existing fans with commercially available fans with the same capacity but higher efficiency, annual savings of \$11,152 (\$18.6/sow) can be attained. Exhaust fans during winter greatly contribute to heat loss and thus require operation of space heaters to maintain the set-point temperature in the production area.

By using a heat exchanger, heat can be recovered from ventilation air during winter and can reduce the operating time of the space heater. In the applied conservation measure, an air-to-air cross-flow heat exchanger with effectiveness of 0.7 was used and resulted to \$21,650 (\$36/sow) annual savings. The use of heat exchanger eliminates the need for the space heater in some situations. In actual application, the barn would still require a space heater where extreme conditions (i.e. very low temperature) can occur. Furthermore, the simulated values were based on the assumptions that the room was filled to capacity (which was not always the case), and that the total heat produced based on equations developed by Pedersen (2002) was accurate.

The actual operation of the heater will depend on the accuracy of manufacturer specified data on effectiveness of heat exchanger. Effectiveness of heat exchangers varies from 0.45 to 0.70. A sensitivity analysis was done to determine the operation of the heater using heat exchangers with different effectiveness as shown in Appendix J. Using heat exchanger with effectiveness of 0.45, only nursery rooms require supplemental heating from December to January. This implied that savings can be maximized by using heat exchanger with higher effectiveness for all rooms. Savings can be maximized if the heat exchanger was installed on the rooms where heater runs more often due to higher temperature set-point like nursery rooms. Applying energy conservation on space heating by using a propane-gas fired radiant heater would reduce the fuel consumption by 52,702 m³/yr (87.8 kWh/sow) or \$17,245/yr (\$28.70/sow) for this simulated barn.

6 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The following conclusion can be drawn from the study:

- An up-to-date information is needed and this research conducted survey on the individual barns with information on the production data and other management practices employed in the surveyed barn. The results of the survey showed that the average energy cost (electricity and gas) per animal marketed is \$6.80 for farrow-to-finish barns, \$1.70 for grow-finish barns, \$0.60 for nursery and \$1.90 for farrow-wean barns. Benchmark information is important to swine producers in assessing the performance of their business if they are within the industry standard. This serves as an indicator if they are doing well or if they need to revised existing energy management plans.
- Energy audit revealed that the areas where improvements can be made are the lights, creep heating system, space heating and feed motors. The results also showed that ventilation and space heating were the specific areas where energy reduction can be maximized by implementing energy saving strategies. Creep heating system was also a major contributor in energy consumption in farrowing rooms for all barns, thus, an efficient system and management practices will maximize the energy savings. Management practices in using heat lamps (i.e. 3 days for Barn A and 1 day for Barn B) in combination with heat pads should be taken into consideration. A well managed creep heating system can significantly reduced the energy consumption as demonstrated in the simulation part of this study.
- Based on the results of the energy survey, negative correlation between energy consumption and indoor air quality was observed. This implies that the high concentration of gases can be attributed to low ventilation rate and vice versa. High

ventilation rate during summer and minimum ventilation rate during winter was observed. This is expected as the heat generated during summer is expelled through the exhaust fan to provide good indoor air quality and prevent heat stress on pigs. In winter, lower ventilation rate is set to prevent cold draft but enough to keep the level of the noxious gases at allowable concentration level. Therefore, higher gas concentration was observed in winter than in summer. On both weather conditions, gas concentrations are within allowable limit set by OSHA.

- Operation of the fans and the heaters were modeled based on the principle of heat transfer and thermodynamics. The model simulates the electrical energy and natural gas consumption for the simulated barn and percent difference for most of the equipment is within 10%. This error can be attributed to instrument accuracy or assumptions made in the model developed. Therefore, the model used had the capability predict the energy consumption in any type of barn. This will serve as a guide to swine producers in energy management.
- The use of energy efficient equipment reduced the energy consumption and can recoup the investment within 1 to 3 years upon implementing such strategy. Energy conservation strategies applied to lighting, creep heating, recirculation fans, exhaust fans, feed motor and heat recovery, can attain an average annual savings of 25,957 kWh (43 kWh/sow), 47,391 kWh (79 kWh/sow), 9,872 kWh (16 kWh/sow), 118,890 kWh (198 kWh/sow), 1,846 kWh (3 kWh/sow), and 74,952 m³ (125 m³/sow), respectively.
- Heat exchanger's effectiveness greatly affects the energy reduction or savings associated with installing it. However, sensitivity analysis done showed that even at a lower effectiveness of 0.45, no supplemental heat is required for other rooms except for nursery room.

6.2 Recommendations

The following list summarizes future work for different research area.

- A more representative data can be achieved by conducting survey for other barns not covered in this research. A larger sample size can be selected which would improve the industry average data computed on energy consumption. Also, energy information should continually be updated as the market condition changes. Updated benchmark information can help producer adapt to the changing environment of the swine industry.
- Energy audit should be conducted for period longer than seven days (i.e. full summer and winter months) to accurately determine the variation of energy consumption for the entire year especially for fans and heaters.
- A user-friendly software should be developed based on the simulation part of this research. This can be used by swine producers in keeping track of their energy consumption and in deciding what energy conservation strategies they can implement in their barn given certain circumstances. On the other hand, the software can also be configured to individual barns so as to address barn specific issues such as management practices which can be variable from barn to barn.

REFERENCES

- Albright, L. D. 1990. Environment control for animal and plants. The American Society of Agricultural Engineers. St. Joseph, Michigan.
- Andries, B. 2006. Preparing your Barn for Summer and Winter. <http://www.thepigsite.com> Accessed January 7, 2007.
- ASHRAE Handbook – Fundamentals. 2005. SI Edition. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, Georgia.
- Bantle, M.R. and E.M. Barber. 1989. Energy simulation of a poultry house using DOE 2.1C. Paper No. 894085, Canadian Society of Agricultural Engineers. Quebec city, Quebec.
- Barber, E. M. 1991. Design of heating and ventilation systems for cold-climate livestock housing. Cold-climate Seminar Proceedings. ASHRAE Region XI Chapter Regional Conference, ASHRAE, Georgia.
- Barber, E.M., H.L. Classen and P.A. Thacker. 1989. Energy Use in the Production and Housing of Poultry and Swine – An Overview. Canadian Journal in Animal Science 69:7-21.
- Barber, E.M. and R.J. Ford. 1989. Field evaluation of an air-to-air heat exchanger in a swine weanling room. Saskatchewan Agricultural Research Fund Board, Saskatchewan Agriculture, Canada.
- Barber, E. M. and J. O. Ogilvie. 1980. Simulation of dynamic livestock environment: GASP IV model. Paper No. 80-212, Canadian Society of Agricultural Engineers. Ottawa, Ontario.
- Bliss, R. J. 1961. Atmospheric radiation near the surface of the ground. Solar Energy 5(3): 103.
- Boris, R. 1986. Electric energy versus coal, propane and oil for hutterite colonies. CSAE paper no. 86-401. Canadian Society of Agricultural Engineers. Saskatoon, Saskatchewan.
- Boris, R.E. 2008. Energy Savings with Heat Pads and Lighting. Advances in Pork Production Vol. 19, p. 49. Department of Agricultural, Food and Nutritional Science, University of Alberta. Edmonton, Alberta.
- Brandl, T.M, J.A. Nienaber, H. Xin and R.S. Gates. 2004. A Literature Review of Swine Heat Production. Transactions of American Society of Agricultural Engineers. Vol. 4 (1): 259-270.
- Camp, R. 1989. The search for industry best practices that lead to superior performance, Productivity Press. USA
- Canada Plan Service. 2006. CPS 3952 – Barn lighting. Ontario Ministry of Agriculture, Food & Rural Affairs. Ontario, Canada. [http:// www.cps.gov.on.ca](http://www.cps.gov.on.ca). Accessed March 4, 2007.

Canadian Agri-Food Research Council (CARC). 1993. Recommended code of practice for care and handling of farm animals: Pigs. Ottawa, Ontario.

Christianson, S.K., S. P. Lemay, C. Lague, J. F. Patience and E. M. Barber. 2002. Moisture Production from Grower-finisher Pigs – Field Measurements Compared with Theoretical Values. ASAE Paper No. 024183. Annual International Meeting/CIGR. Chicago, Illinois.

Clarke, S. and R. Chambers. 2006. Energy Efficient Swine Lighting. <http://www.omafra.gov.on.ca>. Accessed December 10, 2006.

Cooper, C.D and F.C. Alley. 2002. Air pollution control, A design approach. 3rd Ed. Waveland Press, Inc. USA.

Donham, K.J. 1990. Relationships of air quality and productivity in intensive swine housing. *Agri-Practice* 10 (6): 15-26.

Driggers, L.B. 1976. Energy consumption in swine confinement buildings. ASAE paper No. 76-4537. American Society of Agricultural Engineers. Chicago, Illinois.

Energy Publications. 2006. Energy Efficiency Trends in Canada, 1990 to 2004. Office of Energy Efficiency. Natural Resources Canada. Ottawa, Ontario.

Fehr, R.L. 1992. Energy Conservation in Ventilating and Heating Swine Buildings. Purdue University. Cooperative Extension Service. West Lafayette, Indiana.

Ford, R.J. and E.M. Barber. 1988. Survey of electrical energy use in pig production in Saskatchewan. Departmental Research Report, Agricultural Engineering Department, University of Saskatchewan, Saskatoon, Saskatchewan.

George Morris Center, Canadian Pork Market Review. <http://www.georgemorris.org>. Accessed December 7, 2007.

Harder, R. 2008. Visual Management and Energy Consumption on Hog Farms. *Advances in Pork Production* Vol. 19, p. 49. Department of Agricultural, Food and Nutritional Science, University of Alberta. Edmonton, Alberta.

Heinonen, J. and J. Jokisalo. 2005. Electricity Consumption Calculation of Ventilation Systems. Energy efficiency calculation of buildings (RET) project. Helsinki University of Technology, HVAC-laboratory, Espoo, Finland.

Huffman, H. and R. MacDonald. 2006. Energy Efficiencies – Strategies for minimizing utility costs in the barn. London Swine Conference – Thinking Globally, Acting Locally. Ontario Ministry of Agriculture and Food. London, Ontario.

Hydro One Network. 2006. Heating and Cooling. <http://www.hydroonenetworks.com>. Accessed December 10, 2006.

- Khakbazan, M. 1999. A Comparative Study of Energy Use in Hog Barns on the Prairies. Canadian Agricultural Energy End Use Data and Analysis Center. Saskatoon, Saskatchewan.
- Lambert, M., S.P. Lemay, E.M. Barber, T.G. Crowe and L. Chenard. 2001. Humidity Control for Swine Buildings in Cold Climate – Part 1: Modeling of three control strategies. Canadian Biosystems Engineering. 43(5): 29 -36.
- Lemay, S.P. 1999. Barn management and control of odours. Advances in Pork Production Vol. 10 pp. 81. University of Alberta. Edmonton, Alberta.
- MacDonald, R.D. 1984. Analysis of an air-to-air heat exchanger on a hog farm: Better-Air B-400. Ontario Ministry of Agriculture and Food. Toronto, Ontario.
- MacDonald, R.D. 1985. Heat recovery from dairy barn ventilation air. Paper No. 85-406 Canadian Society of Agricultural Engineers. Guelph, Ontario.
- MacDonald, R. 2002. Saving Money by Maximizing Energy Use Efficiency in Swine Production. Advances in Pork Production. Volume 13, p. 99. Department of Agricultural, Food and Nutritional Science, University of Alberta. Edmonton, Alberta.
- MacDonald R. and M. Armstrong. 2002. Pig Barns, Energy Efficiency, the Kyoto Protocol and Your Bottom Line. Canadian Pork Council. Ottawa, Ontario.
- MacDonald, R., T. Feldmann and M Wigglesworth. 2000. Comparison of Heat Lamp to Heat Pad Creep Heat in Farrowing Units. Swine Housing Conference Proceedings. Des Moines, Iowa.
- Marquis, A. and C.N. Hinkle. 1974. Simulation study of constant rate winter ventilation for grow-finishing swine. Canadian Agricultural Engineering Vol. 16. No.2. St. Anne de Bellevue, Quebec.
- McQuiston, F.C. and J.D. Parker. 1994. Heating, Ventilating and Air-Conditioning – Analysis and Design. Fourth Edition. John Wiley and Sons, Inc, USA. p.100-136.
- Meyer, V.M. 1983. Field tests of swine building heat exchangers. Paper No. 83-4071, American Society of Agricultural Engineers. Bozeman, Montana.
- Morsing, S., S. Pedersen, J. Strom and L. Jacobsen. 2005. Energy Consumption and Air Quality in Growing-Finishing Pig House for Three Climate Regions using CIGR 2002 Heat Production Equations. Agricultural Engineering International: Commission Internationale du Genie Rural (CIGR) E-journal Vol. 8. <http://journals.sfu.ca/cigr/index.php>. Accessed February 23, 2008.
- National Energy Board Publication. 2006. Energy Pricing Information for Canadian Consumers – Current Market Conditions. Publications Service. Calgary, Alberta.

Natural Resources Canada Publication. 2006. Trends in Canada's Greenhouse Gas Emissions 1990–1995. <http://www.nrcan.gc.ca>. Accessed December 10, 2006.

Neinaber and G.L. Hahn. 1988. Environmental temperature influences on heat production of ad-lib-fed nursery and growing-finishing swine. International Livestock Environment Conference Proceedings. American Society of Agricultural Engineers. St. Joseph, Michigan.

Nesbary, D.K. 2000. Survey Research and World Wide Web. Pearson Education Company, Boston, Massachusetts.

Occupational Safety and Health Administration. 1989. OSHA Safety and Health Standards. Occupational Safety Health Admin., US Department of Labor, Washington, District of Columbia.

Ogilvie, J. O., Y. Zhang, and E. M. Barber 1988. Simulation of the dynamic thermal environment in a swine barn. Paper No. 88-4032. American Society of Agricultural Engineers. St. Joseph, Michigan.

OMAFRA, 2006. The value of doing an energy audit on your farm. Better Pork, February edition. pp. 29-30.

Overhults, D.G. and R.L. Fehr. 1986. Predicting heat exchanger energy savings. Paper No. 86-4002. American Society of Agricultural Engineers. St. Joseph, Michigan.

Pork Industry Handbook (PIH). 2000. Troubleshooting Ventilation Systems. Michigan State University Extension Bulletin E-2574. St. Joseph, Michigan.

Prairie Swine Center Inc. 2001. Energy Efficiency in Barns Part I. Publication No. 01-01. Saskatoon, Saskatchewan.

Prairie Swine Center Inc. 2004. Energy Efficiency in Barns Part II. Publication No. 01-00204. Saskatoon, Saskatchewan.

Pedersen, S., S. Morsing, and J. Strom. 2005. Simulation of Heat Requirement and Air-Quality in Weaner Houses for Three Climate Regions using CIGR 2002 Heat Production Equations. Commission Internationale du Genie Rural (CIGR) E-journal Vol. 8. <http://journals.sfu.ca/cigr/index.php>. Accessed May 21, 2008.

Pedersen, S. 2002. Heat and Moisture Production of Pigs on Animal and House Level. Paper No. 024178. American Society of Agricultural Engineers. Chicago, Illinois.

Pedersen, S. and K. Sallvik. 2002. Climatization of Animal Houses – Heat and Moisture Production of Pigs on Animal and House Level. International Commission of Agricultural Engineering. Research Center Bygholm, Danish Institute of Agricultural Sciences, Horsens, Denmark.

Quinn, G.P. and M.J. Keough. 2002. *Experimental Design and Data Analysis for Biologists*. Cambridge University Press. New York, New York.

Renaudeau, D., E. Huc, M. Kerdoncuff and J. Gourdine. 2006. Acclimation to high ambient temperature in growing pigs: affects of breed and temperature level. Institut National de la Recherche Agronomique. Guadeloupe French West Indies, France.

Ricalde, R.H.S. and L. Jean. 2000. The effect of tropical outside temperature on productive performance and grazing behavior of sows kept in an outdoor system. Wye College, University of London, UK.

Riskowski, G.L. and D.S. Bundy. 1988. Effect of air velocity and temperature on weanling pigs. International Livestock Environment Conference Proceedings. American Society of Agricultural Engineers. St. Joseph, Michigan.

Statistics Canada. Hog Statistics First quarter 2008. Catalogue no. 23-010-X, vol. 7, no. 2. Ottawa, Ontario. <http://www.statcan.ca>. Accessed May 12, 2008.

Stowell, R.R., H. Keener, D. Elwell, T. Menke and S. Inglis. 2001. Indoor air quality and pig performance within a high-rise hog facility. ASAE Paper No. 701P0201. American Society of Agricultural Engineers. Louisville, Kentucky.

Sun, G. 2005. Monitoring and Modeling Diurnal & Seasonal Odour and Gas Emission Profiles for Swine Barn. M.Sc. Thesis. University of Saskatchewan. Saskatoon, Saskatchewan.

Timmons, M.B. 1990. How does natural ventilation work and why? Paper No. 90-4551. American Society of Agricultural Engineers. Chicago, Illinois.

Thumann, A. and W.J. Younger. 2005. *Handbook of energy audits*. Fairmont Press, Lilburn, GA. Vaisala Instruments Catalog. 2007. Vaisala Carbocap Sensor Technology for Stable Carbon Dioxide Measurement. Helsinki, Finland.

Van Dyke, J., J. Rogers and H. Adams. 2007. *Fundamentals of mathematics*. Thomson Brooks/Cole. Belmont, California.

Wang, Y. 2007. Monitoring and Modeling of Diurnal and Seasonal Odour and Gas Emissions from Different Types of Swine Rooms. M.Sc. Thesis. University of Saskatchewan. Saskatoon, Saskatchewan.

Wilhelm, L.R. and D.B. McKinney. 2001. Environmental Measurements in Production Swine Facilities. *Applied Engineering in Agriculture* Vol. 17 (5):669-675. American Society of Agricultural Engineers. St. Joseph, Michigan.

Wilhelm, L.R., J.M. Milner, S.D. Snyder and D.B. McKinney. 2001. An Instrumentation System for Environmental Measurements in Broiler and Swine Housing. *Applied Engineering in Agriculture* Vol. 17 (5):677-681. American Society of Agricultural Engineers. St. Joseph, Michigan.

Wheeler, E.F., R.E. Graves, J.L. Zajackowski, J.T. Tyson, D.F. McFarland and P. Richie. 2001. Protocol for Determination of Environmental Parameters in Animal Housing. *International Livestock Environment Conference Proceedings*. American Society of Agricultural Engineers. St. Joseph, Michigan.

Zhang, Y. 1989. Analysis of heating and ventilating control strategies for cold-climate livestock housing. Ph.D. Dissertation, University of Saskatchewan. Saskatoon, Saskatchewan.

Zhang, Q., J. Wong Li, H. Xin, M.L. Connor and R. Boris. 2004. Comparing the effect of heat mats and heat lamps in swine farrowing barns. *Biosystems Engineering*, University of Manitoba. Winnipeg, Manitoba.

Li, Z. 2000. Simulation of the dynamic thermal environment of a livestock housing airspace. M.Sc. Thesis. University of Saskatchewan. Saskatoon, Saskatchewan.

APPENDIX A

SURVEY QUESTIONNAIRE



A Survey on Energy Consumption and Conservation Strategies Employed in Typical Swine Barns

SECTION I BARN INFORMATION

1.1 Name of barn

1.2 Land location of barn

1.3 What type of barn do you operate?

Farrow-to-finish Finish

Farrow Nursery

1.4 What is the size of your operation?

Monthly Average	Farrow	Gestation	Nursery	Grower	Finisher
Number of rooms					
Number of pens per room					
Number of pigs per pen					
Average mortality rate, %					
Average body weight (IN), kg					
Average body weight (OUT)*, kg					

*Average body weight (OUT) is the average market/shipping weight.

SECTION 2

PRODUCTION DATA

Date	Finishers		Weanlings		Culled sows/gilts/boars	
	Quantity sold	Average Weight, kg	Quantity sold	Average Weight, kg	Quantity sold	Average Weight, kg
Jul-2003						
Aug-2003						
Sept-2003						
Oct-2003						
Nov-2003						
Dec-2003						
Jan-2004						
Feb-2004						
Mar-2004						
Apr-2004						
May-2004						
Jun-2004						
Jul-2004						
Aug-2004						
Sept-2004						
Oct-2004						
Nov-2004						
Dec-2004						
Jan-2005						
Feb-2005						
Mar-2005						
Apr-2005						
May-2005						
Jun-2005						
Jul-2005						
Aug-2005						
Sept-2005						
Oct-2005						
Nov-2005						
Dec-2005						
Jan-2006						
Feb-2006						
Mar-2006						
Apr-2006						
May-2006						
Jun-2006						

SECTION 3

ENERGY EXPENSES DATA

Date	Billing Period	Electricity, (\$)	Natural Gas, (\$)	Propane Gas, (\$)	Coal (\$)	Other sources (\$)
Jul-2003						
Aug-2003						
Sept-2003						
Oct-2003						
Nov-2003						
Dec-2003						
Jan-2004						
Feb-2004						
Mar-2004						
Apr-2004						
May-2004						
Jun-2004						
Jul-2004						
Aug-2004						
Sept-2004						
Oct-2004						
Nov-2004						
Dec-2004						
Jan-2005						
Feb-2005						
Mar-2005						
Apr-2005						
May-2005						
Jun-2005						
Jul-2005						
Aug-2005						
Sept-2005						
Oct-2005						
Nov-2005						
Dec-2005						
Jan-2006						
Feb-2006						
Mar-2006						
Apr-2006						
May-2006						
Jun-2006						

APPENDIX B

SELECTION OF BARNs TO BE MONITORED

B.1 Selection criteria

The selection criteria based on profile of 366 Saskatchewan swine barns in the SaskProk database. This profile was used to rank the surveyed barns that represent the most typical swine barn (i.e. high frequency distribution on type and size of operation). Tables B.1 to B.3 show the score for each type of barns and size of operations. Equations B.1 and B.2 were used to compute the score based on the \$/pig sold.

Table B.1 Selection criteria: type of operation and percent population of swine industry

Type of operation	No. of barns	Frequency Distribution, %	Score
1. Farrow to Finish	202	55.2	5
2. Grow-Finish	113	30.9	3
3. Farrow to Wean	34	9.3	1
4. Nursery	17	4.6	0.4
TOTAL	366	100	

Note: Score of 3 for grow-finish barn was computed as $(30.9/55.2)*5$ and rounded off.

Source: Saskpork, 2007

Table B.2 Selection criteria: size of operation for farrow-finish and farrow-wean

Size of Operation (No. of sows)	Farrow-Finish			Farrow-Wean		
	No. of barns	Frequency Distribution, %	Score	No. of barns	Frequency Distribution, %	Score
1. 0 - 100	81	40.0	5	6	17.6	3
2. 100 - 250	29	14.4	2	4	11.8	2
3. 250 - 600	71	35.2	4	2	5.9	1
4. 600 - 2,000	21	10.4	1	6	17.6	3
5. 2,000 - 4,000	0	0	0	11	32.4	5
6. 4,000 +	0	0	0	5	14.7	2
TOTAL	202	100		34	100	

Note: Score of 2 for farrow-finish barn with size of 110-250 sow operation was computed as $(14.4/40)*5$ and rounded off. Score of 3 for farrow-wean barn with less than 100-sow operation was computed as $(17.6/32.4)*5$ and rounded off.

Source: Saskpork, 2007

Table B.3 Selection criteria: size of operation for grow-finish and nursery

Size of Operation (No. of feeders and weanlings)	Grow-Finish			Nursery		
	No. of barns	Frequency Distribution, %	Score	No. of barns	Frequency Distribution, %	Score
1. 0 - 500	37	32.7	5	0	0.0	0
2. 500 - 1,000	14	12.4	2	0	0.0	0
3. 1,000 - 2,000	16	14.2	2	0	0.0	0
4. 2,000 - 4,000	7	6.2	1	2	11.8	1
5. 4,000 - 8,000	12	10.6	2	8	47.0	5
6. 8,000 +	27	23.9	4	7	41.2	4
TOTAL	113	100		17	100	

Note: Score of 2 for grow-finish barn with size of 500-1000 hog operation was computed as $(12.4/32.7)*5$ and rounded off. Score of 4 for nursery barn with more than 8000-nursery operation was computed as $(41.2/47)*5$ and rounded off.

Source: Saskpork, 2007

For least efficient and most efficient barns, the score based on energy cost is expressed in equations B.1 and B.2, respectively.

$$R_{ec} = \frac{EC_{indy}}{EC_{leb}} \times 5 \quad (B.1)$$

$$R_{ec} = \frac{EC_{meb}}{EC_{ind}} \times 5 \quad (B.2)$$

where:

R_{ec} is the score based on energy cost

EC_{ind} is the energy cost per animal marketed for individual barn

EC_{leb} is the energy cost per animal marketed for least efficient barn

EC_{meb} is the energy cost per animal marketed for most efficient barn

Table B.4 and B.5 show the top barns from each category. These barns were contacted and permission to conduct energy audit was sought. However, only two barns can be selected from each category due to limited resources. Thus, permission was sought from the barns in Table B.4 and B.5 from top to bottom until the first two barns per category agreed to participate.

Table B.4 Selection of two most efficient barns that represents a high percentage population of the swine industry

Rank	Barn Code	Type of operation	For F-F and F-W (number of sows); for G-F and N (number of feeders + weanlings)	A V E R A G E, \$/100kg pig	SCORE				
					Type of Operation	Size of Operation	Relative percentage of the lowest \$/100-kg-pig sold per category	Relative percentage of the lowest \$/100-kg-pig sold for the entire surveyed barns	T O T A L
1	D	Grow-to-Finish	30,461	\$1.17	3.0	4.0	5.0	5.0	17.0
2	BSID	Grow-to-Finish	28,672	\$1.34	3.0	4.0	4.4	4.4	15.8
3	PC	Farrow-to-finish barns With Feedmill	428	\$3.56	5.0	4.0	5.0	1.6	15.6
4	BSIH	Farrow-to-finish barns With Feedmill	360	\$3.99	5.0	4.0	4.4	1.5	14.9
5	BSIM	Grow-to-Finish	38,925	\$1.51	3.0	4.0	3.9	3.9	14.8
6	B	Farrow-to-finish barns With Feedmill	262	\$4.27	5.0	4.0	4.1	1.4	14.5

Note: The computation was done to rank the barns based on the 5-point score. Barn B is a farrow-to-finish barn which comprised 55.2% of the total swine barn population in Saskatchewan based on type of operation and given a 5-point score. It is also a 262-sow barn which comprised 35.2% of the total swine barn population in Saskatchewan based on size of operation and given a 4-point score. The average energy cost per 100-kg animal marketed for Barn B is \$4.27 while the most efficient barn in the farrow-finish with feedmill category is \$3.54. Thus, $(\$3.54/\$4.27)*5$ -point scale is 4.1 which was the score given for Barn B. The lowest \$/100-kg pig sold for the 28 swine barns is \$1.17, thus, Barn B was given 1.4 points. Adding up all the scores, the total score for Barn B is 14.5 points.

Table B.5 Selection of two least efficient barns that represents a high percentage population of the swine industry

Rank	Barn Code	Type of operation	For F-F and F-W (number of sows); for G-F and N (number of feeders + weanlings)	A V E R A G E, \$/100kg pig	SCORE				
					Type of Operation	Size of Operation	Relative Percentage to the highest \$/100-kg-pig sold per category	Relative Percentage to the highest \$/100-kg-pig sold for the entire surveyed barns	T O T A L
1	A	Farrow-to-finish barns Without Feedmill	600	\$7.17	5.0	4.0	5.0	2.0	16.0
2	HC	Farrow-to-finish barns With Feedmill	320	\$8.86	5.0	4.0	4.3	2.5	15.8
3	UF	Farrow-to-finish barns Without Feedmill	551	\$6.58	5.0	4.0	4.6	1.8	15.4
4	C	Farrow-to-wean	1,220	\$17.83	1.0	3.0	5.0	5.0	14.0
5	FGTN	Farrow-to-finish barns With Feedmill	1,068	\$10.22	5.0	1.0	5.0	2.9	13.9

Note: The computation was done to rank the barns based on the 5-point score. Barn C is a farrow-to-wean barn which comprised 9.3% of the total swine barn population in Saskatchewan based on type of operation and given a 1-point score. It is also 1,220-sow barn which comprised 17.6% of the total swine barn population in Saskatchewan based on size of operation and given a 3-point score. The average energy cost per 100-kg animal marketed for Barn C is \$17.83 while the least efficient barn in the farrow-wean barn category was also the same barn. Thus, $(\$17.83/\$17.83)*5$ -point scale is 5 which was the score given for Barn C. The highest \$/100-kg pig sold for the 28 swine barns is \$17.83, thus, Barn B was given 5 points. Adding up all the scores, the total score for Barn C is 14 points.

APPENDIX C

INSTRUMENTS USED IN ENERGY AUDIT

C.1 Instruments used for electrical energy measurement

C.1.1 Clamp-on Transducers (CT) Potential Transformer (PT) and Energy logger

The energy logger is equipped with three modules which convert many signals from third party sensors. Each module can accommodate 2 sensors. The sensors deployed in the barn are five (5) clamp-on transducers to measure current from each component (i.e. heat pad, heat lamps, motor, lights, fans, etc) and one (1) potential transformer to measure the voltage available in the barn's outlet. This logger is set to collect data every 10 minutes. Figure C.1 shows the energy logger, current transducer and voltage transformer.



a) Energy Logger



b) CT



c) PT

Figure C.1 Clamp-on transducers (CT), potential transformer (PT) and energy logger

C.1.2 Split-core Current Transducers (CTs) and datalogger

Another type of datalogger and current sensors were used to measure the current of feed motor at a shorter interval of 1 minute. The Hobo U12 datalogger accepts 4-20 mA current signals from the Onset CTV split-core transducers. Figure C.2 shows the datalogger and sensors.



Figure C.2 Split-core current transducers (CTs) and datalogger

A potential transformer (PT) accepts one terminal voltage applied to one of its windings and by induction produces a second terminal voltage in the other winding. The ratio between the two voltages is inversely proportional to the ratio of the numbers of turns in the respective windings. For current transformer (CT), the primary is in series with the load current flowing through the circuit. The CT primary consists of only a single turn while the secondary contains many turns and develop a higher voltage than the primary. When a load is connected to the secondary terminals, current flows in that circuit and, as in any other transformer, will be related to the primary current in inverse ratio to the numbers of turns in the two windings. Such secondary CT loads are either low-voltage meters to monitor amperage.

Current sensor was calibrated by measuring the current of equipment with different power scores. The reading from the logger is within $\pm 4\%$ and $\pm 1\%$ of equipment's power rating for CTV-series and T-mag series, respectively. This error is due to the accuracy of the instrument.

C.2 Instruments used for natural gas and propane energy measurement

The gas meter as shown in Figure C.3 is a diaphragm type meter used in submetering applications. The two types of meter used in the barn monitoring have a capacity of 250 ft³/h and 425 ft³/h. The gas flow is controlled by internal valves and the chambers formed by the movable diaphragm alternately fill and release gas resulting to a near continuous flow through the meter. As the diaphragm contracts and expand, crank lever convert the linear motion into rotary motion of a crankshaft that serves as the volume flow indicator. The type of counter used in the barn monitoring part of this project is an odometer-like counter mechanism. (Canadian Meter Company, 2003).

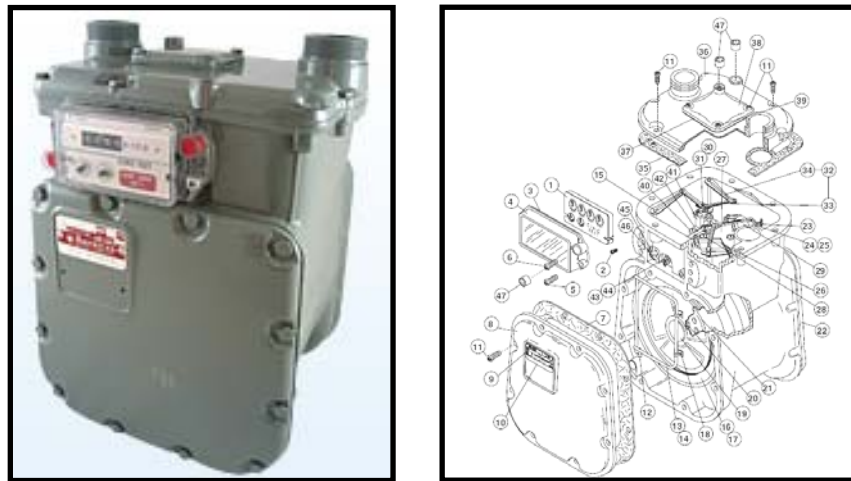


Figure C.3 Natural gas and Propane gas meters

C.3 Instruments used for indoor air quality (IAQ) parameters measurement

C.3.1 Temperature and Relative Humidity Sensor

Hobo U12 datalogger as shown in Figure C.4 has internal temperature sensor (10K thermistor) and the relative humidity sensor (capacitive-type). The operation of thermistor is based on the principle that metal oxides change resistance with the change in temperature. Thermistor decreases in resistance as the temperature increases. This change in resistance is detected by meter where it is converted to a temperature reading. The capacitive-type RH sensor is consists

of a thin layer of water absorbent polymeric material. This layer is covered with a porous conductive layer. As the relative humidity increases, the water content of the polymer increases. The capacitive sensors sense water by applying a rapidly reversing (AC) voltage across the plates and measuring the current that passes. The measured current is converted to the corresponding relative humidity.



Figure C.4 Temperature and relative humidity sensor

C.3.2 Ammonia (NH₃) and Hydrogen Sulfide (H₂S) Monitors

Ammonia (NH₃) and hydrogen sulphide (H₂S) concentrations were measured using PAC 7000 shown in Figure C.5. PAC 7000 is a datalogger with internal electrochemical sensor. Electrochemical sensor consists of a sensing electrode and a counter electrode separated by a thin layer of electrolyte. This reacts to the gas of interest producing an electrical signal proportional to the gas concentration.



Figure C.5 Ammonia (NH₃) and hydrogen sulfide (H₂S) monitors

Carbon dioxide (CO₂) concentration was measured using the Vaisala transmitter with a non-dispersive infrared (NDIR) sensor and output connection connected to a logger that accepts 4-20 mA signal as shown in Figure C.6. An infrared source at the end of the measurement chamber emits light into the gas chamber, where any carbon dioxide gas present absorbs a part of the light at its characteristic wavelength. The Fabry-Perot Interferometer (FPI) is made of silicon. The FPI interference filter is electrically tuned so that its pass band coincides with the absorption wavelength of carbon dioxide. The IR detector measures the strength of the signal that passes through. After the pass band of the FPI is shifted to a wavelength where no absorption occurs. This provides the reference signal. The ratio of these two signals, one at the absorption wavelength and the other at the reference wavelength, indicates the degree of light absorption in the gas and thus the gas concentration (Vaisala, 2007).

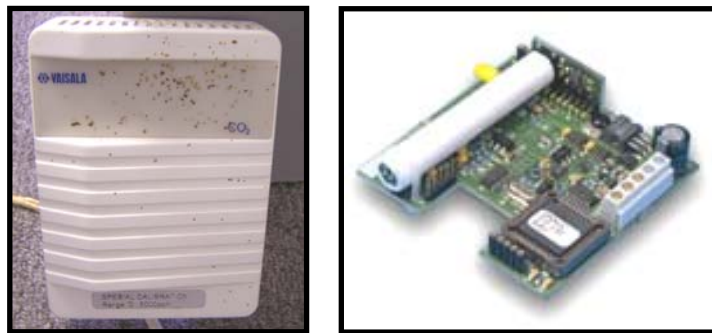


Figure C.6 Carbon dioxide (CO₂) transmitter

Gas sensors for ammonia, hydrogen sulphide, and carbon dioxide were calibrated prior to installing it inside the barn. The calibration gas (i.e. 25 ppm H₂S, 50 ppm NH₃ and 2000 ppm CO₂) is passed through the sensor at 0.5 L/min. The reading from the logger is within $\pm 5\%$ of the span gas. The error is due to instrument accuracy.

APPENDIX D

STATISTICAL ANALYSIS

D.1 Statistical Analysis of Survey Results

D.1.1 Two sample comparison t-statistics

To compare the energy cost between two types of barns, a total of 6 sets of comparison were made as shown in Table D.1. To determine the value of t , the following equation was used by the SAS program.

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - m}{s \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (D.1)$$

$$s^2 = \frac{(n_1 - 1) s_1^2 + (n_2 - 1) s_2^2}{n_1 + n_2 - 2} \quad (D.2)$$

where:

s^1 & s^2 is the variance of two samples

n_1 & n_2 is the number of data for two samples

$\bar{x}_1 - \bar{x}_2$ is the mean of the two samples

D.1.2 SAS program code

```
proc ttest data=survey;  
class barn;  
var Ec;  
run;
```

Note that the barn pertains to the type of barn and Ec is the energy cost per animal marketed.

D.1.3 SAS results

Table D.1 Statistical results of two sample t-test

Barn Type	Pooled (Pr>t)	Significance (p<0.05)
FF vs Nursery	0.0091	Yes
FF vs GF	0.0003	Yes
FF vs FW	0.0055	Yes
Nursery vs GF	0.0034	Yes
Nursery vs FW	0.0048	Yes
GF vs FW	0.5650	No

D.2 Linear Correlation on fan energy consumption and indoor air quality parameters

Correlation coefficient (r) is computed based on the following equation.

$$r = \frac{\Sigma xy - \frac{\Sigma x \Sigma y}{n}}{\sqrt{\left(\Sigma x^2 - \frac{(\Sigma x)^2}{n}\right) \left(\Sigma y^2 - \frac{(\Sigma y)^2}{n}\right)}} \quad \text{D.3}$$

The range of correlation coefficient is from -1 to 1. The following table shows the interpretation of the r value.

Table D.2 Interpretation of coefficient of correlation

Range of r value	Interpretation
- 1 to - 0.67	Strong and negative correlation
- 0.66 to - 0.34	Medium and negative correlation
- 0.33 to - 0.01	Weak and negative correlation
0 to 0.32	Weak and positive correlation
0.33 to 0.65	Medium and positive correlation
0.66 to 1	Strong and positive correlation

Source: Quinn and Keough, 2002

APPENDIX E

SOL-AIR TEMPERATURE COMPUTATION

One factor that needs to be taken into consideration in the calculation of building heat transmission is the effect of solar radiation, radiant energy exchange with the sky and convective heat exchange with the outdoor air. Sol-air temperature is the equivalent outdoor air temperature that, in the absence of all radiation changes gives the same rate of heat entry into the surface (ASHRAE 2005). The sol-air temperature equation is as follows:

$$t_e = t_o + \frac{\alpha E_t}{h_o} - \frac{\varepsilon \Delta R}{h_o} \quad (\text{E.1})$$

where:

t_e is the sol-air temperature, K

t_o is the outdoor air temperature, K

α is the absorptance of surface for solar radiation

E_t is the total solar radiation incident on surface, W/m^2

h_o is the coefficient of heat transfer by long-wave radiation and convection at outer surface, $\text{W}/(\text{m}^2 \text{ K})$

ε_h is the hemispherical emittance of surface

ΔR is the difference between long-wave radiation incident on surface from sky and surroundings and radiation emitted by blackbody at outdoor air temperature, W/m^2

For horizontal surfaces that receive long wave radiation from the sky only, an appropriate value of ΔR is about $63 \text{ W}/\text{m}^2$, so that $\varepsilon = 1$ and $h_o = 17 \text{ W}/(\text{m}^2 \text{ K})$, the long-wave correction term is about 4 K (Bliss 1961).

Because vertical surfaces receive long-wave radiation from the ground and surrounding buildings as well as from the sky, an accurate ΔR is difficult to determine. It is common to assume $\varepsilon \Delta R = 0$ for vertical surfaces.

ASHRAE (2005) recommended $\alpha/h_o=0.026$ for light-colored surfaces and $\alpha/h_o=0.052$ for the maximum value for this parameter, which is used for dark-colored surfaces.

The total surface irradiance (E_t) is the sum of surface direct irradiance (E_D), diffuse irradiance (E_d) and ground-reflected irradiance (E_r). Solar angles (i.e. solar altitude, azimuth and surface incident angles) as shown in Figure E.1 are used to compute for these irradiances.

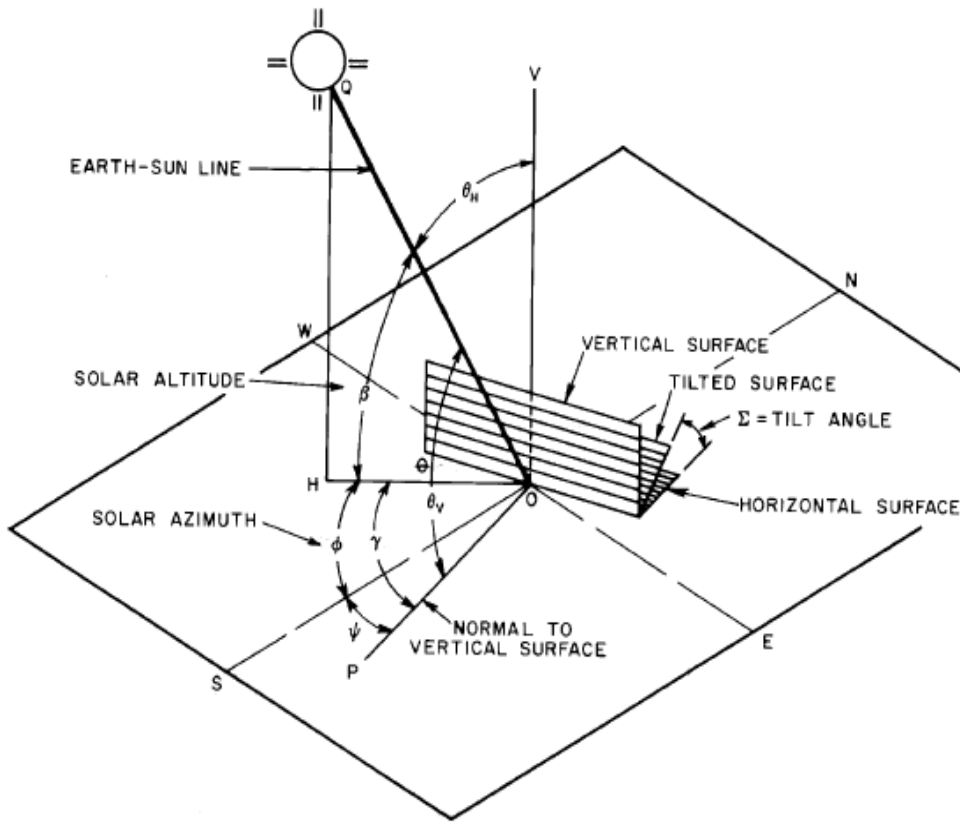


Figure E.1 Solar angle for vertical and horizontal surfaces (source: ASHRAE 2005)

The solar altitude (β) is computed using the following equation.

$$\sin \beta = \cos L \cos \delta \cos H + \sin L \sin \delta \quad (\text{E.2})$$

where:

β is the solar altitude, degrees

L is the latitude, degrees

δ is the solar declination, degrees

H is the hour angle, degrees

The values of solar declination (δ) can be found in ASHRAE handbook chapter 31. The hour angle can be computed using the following equation.

$$H = 15 (AST - 12) \quad (\text{E.3})$$

where:

H is the hour angle, degrees

AST is the apparent solar time, decimal hours

$(AST - 12)$ represents the hours of time from local solar noon

The apparent solar time is expressed as follows:

$$AST = LST + \frac{ET}{60} + \frac{(LSM - LON)}{15} \quad (\text{E.4})$$

where:

AST is the apparent solar time, decimal hours

LST is the local standard time, decimal hours

ET is the equation of time, decimal minutes

LSM is the local standard time meridian, decimal degrees of arc

LON is the local longitude, decimal degrees of arc

The local standard time meridian is 60° for Atlantic Standard Time, 75° for Eastern Standard Time, 90° for Central Standard Time, 105° for Mountain Standard Time, 120° for Pacific Standard Time, 135° for Alaska Standard Time and 150° for Hawaii-Aleutian Standard Time. (ASHRAE, 2005)

The values of equation of time (ET) can be found in ASHRAE handbook chapter 31. The hour angle can be computed using the following equation.

The next angle that needs to be determined is the solar azimuth (ϕ).

$$\cos \phi = \frac{(\sin \beta \sin L - \sin \delta)}{(\cos \beta \cos L)} \quad (\text{E.5})$$

where:

ϕ is the solar azimuth, degrees

β is the solar altitude, degrees

L is the latitude, degrees

δ is the solar declination, degrees

The surface-solar azimuth (γ) can be computed using the following equation.

$$\gamma = \phi - \psi \quad (\text{E.6})$$

where:

γ is the surface-solar azimuth, degrees

ϕ is the solar azimuth, degrees

ψ is the surface azimuth, degrees

Incident angle (θ) should be computed as follows.

$$\cos \theta = \cos \beta \cos \gamma \sin \Sigma + \sin \beta \cos \Sigma \quad (\text{E.7})$$

where:

θ is the incident angle, degrees

β is the solar altitude, degrees

γ is the surface-solar azimuth, degrees

Σ is the surface tilt from horizontal, degrees

Horizontal surface has surface tilt of 0 degrees while vertical surfaces (wall) has surface tilt angle of 90 degrees.

After the solar angles are computed, the direct/diffuse/ground-reflected and total solar irradiances were computed. The direct normal irradiance (E_{DN}) was computed based on the following equation if solar altitude is greater than zero ($\beta > 0$). Otherwise, E_{DN} is equal to zero.

$$E_{DN} = \left(\frac{A}{\exp(B/\sin \beta)} \right) CN \quad (\text{E.8})$$

where:

E_{DN} is the direct normal irradiance

A is the apparent solar constant

B is the atmospheric extinction coefficient

β is the solar altitude, degrees

CN is the clearness number multiplier for clear/dry or hazy/humid locations

Values of A, B and CN are given in ASHRAE handbook 2005 chapter 31.

The direct normal irradiance (E_{DN}) is needed in the computation of surface direct irradiance (E_D). If $\cos\theta$ is greater than zero, the surface direct irradiance can be computed using the following equation. Otherwise, E_D is zero.

$$E_D = E_{DN} \cos\theta \quad (E.9)$$

The ratio Y of sky diffuse on vertical surface to sky diffuse in the horizontal surface is computed as follows if $\cos\theta$ is greater than -0.2 . Otherwise, Y is equal to 0.45 .

$$Y = 0.55 + 0.437 \cos\theta + 0.313 \cos^2\theta \quad (E.10)$$

The diffuse irradiance (E_d) for vertical surface is expressed as follows:

$$E_d = C Y E_{DN} \quad (E.11)$$

where:

C is the sky diffuse factor found in ASHRAE handbook chapter 31

Y is the ratio of sky diffuse on vertical to horizontal surface

E_{DN} is the direct normal irradiance

The diffuse irradiance (E_d) for surfaces other than vertical can be computed using the following equation.

$$E_d = C E_{DN} \left(\frac{1 + \cos\Sigma}{2} \right) \quad (E.12)$$

The ground-reflected irradiance can be computed as follows:

$$E_r = E_{DN} (C + \sin\beta) \rho_g (1 - \cos\Sigma) / 2 \quad (E.13)$$

where:

ρ_g is the ground reflectivity given in ASHRAE handbook chapter 31

The total surface irradiance (E_t) is then computed as follows:

$$E_t = E_D + E_d + E_r \quad (\text{E.14})$$

Li (2000) calculated the total solar irradiance for a wide range of latitudes and dates of the year and compared with the value published by ASHRAE in 1997. It was observed that the differences were very small.

APPENDIX F
WEATHER DATA

Table F.1 A 5-year average weather data in Saskatoon (Source: Environment Canada, 2008)

Day	Outside temperature, deg C	Day	Outside temperature, deg C	Day	Outside temperature, deg C	Day	Outside temperature, deg C	Day	Outside temperature, deg C	Day	Outside temperature, deg C
1	-6.1	26	-0.9	51	-7.1	76	2.5	101	1.5	126	20.2
2	4.8	27	-13.5	52	-6.4	77	1.1	102	11.4	127	20.9
3	4.7	28	-4.3	53	-6.1	78	-8.1	103	16.9	128	23.8
4	1.4	29	-14.4	54	-4.7	79	6.8	104	21.9	129	20.7
5	-6.3	30	-6.7	55	-6.4	80	-1.1	105	13.9	130	15.1
6	-4.1	31	-7.5	56	-8.4	81	4.7	106	17.0	131	19.4
7	-6.9	32	-13.9	57	-13.9	82	7.9	107	19.2	132	23.7
8	-6.0	33	-18.5	58	-14.6	83	7.3	108	18.0	133	15.8
9	-8.5	34	-20.9	59	-10.7	84	7.3	109	20.5	134	18.4
10	-8.4	35	-18.5	60	-7.0	85	8.8	110	12.6	135	16.9
11	-21.8	36	-15.3	61	-8.8	86	3.2	111	11.9	136	21.9
12	-20.9	37	-16.7	62	-2.4	87	2.8	112	14.2	137	25.5
13	-15.2	38	-23.3	63	-8.2	88	4.0	113	14.0	138	13.9
14	-22.0	39	-21.1	64	-13.8	89	7.0	114	18.2	139	13.2
15	-12.2	40	-23.0	65	-12.2	90	7.9	115	19.1	140	14.6
16	-4.7	41	-17.0	66	1.9	91	2.5	116	16.8	141	8.9
17	-3.5	42	-16.7	67	2.5	92	-0.4	117	19.8	142	13.0
18	-7.2	43	-22.7	68	2.9	93	-5.9	118	22.8	143	11.6
19	-9.1	44	-19.8	69	2.5	94	-3.6	119	15.6	144	12.8
20	-10.3	45	-18.9	70	0.4	95	-3.2	120	15.1	145	16.0
21	-7.1	46	-2.0	71	5.8	96	-2.4	121	17.0	146	20.2
22	-2.4	47	-4.7	72	1.4	97	2.2	122	21.3	147	24.7
23	-1.1	48	-9.4	73	-6.2	98	6.1	123	24.2	148	17.7
24	-2.1	49	-3.0	74	-5.1	99	6.9	124	15.3	149	12.7
25	1.6	50	-6.6	75	-1.2	100	2.6	125	18.1	150	13.8

Note: Similar data on weather conditions for different barns were obtained from the nearest weather station.

Table F.1 continued...

Day	Outside temperature, deg C	Day	Outside temperature, deg C	Day	Outside temperature, deg C	Day	Outside temperature, deg C	Day	Outside temperature, deg C	Day	Outside temperature, deg C
151	22.1	176	16.1	201	28.4	226	20.0	251	16.0	276	14.3
152	25.6	177	15.0	202	29.3	227	19.9	252	16.7	277	10.0
153	28.6	178	18.1	203	30.8	228	22.0	253	16.9	278	8.6
154	24.6	179	20.0	204	30.5	229	22.1	254	22.8	279	4.8
155	20.7	180	23.7	205	31.0	230	19.0	255	14.5	280	13.6
156	26.1	181	25.5	206	25.4	231	20.0	256	9.6	281	9.3
157	15.4	182	26.5	207	26.9	232	14.9	257	19.2	282	13.2
158	17.6	183	25.9	208	31.4	233	15.1	258	23.5	283	10.0
159	23.0	184	27.3	209	32.3	234	14.2	259	26.3	284	5.4
160	19.2	185	25.4	210	32.9	235	15.3	260	12.2	285	14.9
161	18.9	186	28.9	211	35.0	236	18.8	261	17.5	286	12.5
162	25.4	187	30.6	212	23.7	237	26.9	262	9.5	287	12.0
163	24.4	188	24.8	213	23.5	238	15.2	263	9.2	288	16.8
164	23.0	189	22.1	214	27.1	239	18.2	264	15.2	289	14.1
165	22.7	190	18.6	215	31.0	240	17.8	265	20.9	290	9.6
166	20.5	191	21.2	216	27.5	241	20.2	266	9.7	291	11.4
167	22.8	192	23.2	217	25.3	242	26.2	267	11.6	292	14.4
168	15.7	193	27.5	218	23.0	243	31.3	268	16.3	293	7.9
169	18.9	194	31.0	219	32.4	244	20.5	269	16.3	294	10.0
170	21.1	195	29.8	220	27.5	245	21.4	270	17.0	295	13.6
171	21.4	196	26.4	221	18.6	246	25.4	271	23.4	296	12.3
172	27.5	197	27.2	222	16.3	247	27.6	272	10.4	297	22.1
173	25.4	198	27.9	223	20.2	248	21.8	273	14.3	298	12.5
174	25.6	199	28.5	224	23.6	249	14.6	274	17.4	299	1.9
175	21.5	200	28.1	225	24.1	250	13.0	275	17.8	300	4.8

Table F.1 continued...

Day	Outside temperature, deg C	Day	Outside temperature, deg C	Day	Outside temperature, deg C
301	13.8	326	-2.9	351	-12.6
302	12.6	327	-4.1	352	-11.9
303	7.9	328	-0.9	353	-8.0
304	10.3	329	1.0	354	-10.6
305	9.3	330	-18.2	355	-7.8
306	7.9	331	-15.4	356	-16.7
307	9.0	332	-17.4	357	-11.7
308	5.8	333	-18.2	358	-2.6
309	-0.2	334	-13.8	359	-2.6
310	1.0	335	-16.1	360	-5.0
311	2.6	336	-16.3	361	-7.5
312	4.7	337	-13.2	362	-7.7
313	0.6	338	-13.9	363	-8.4
314	5.4	339	-13.6	364	-13.8
315	6.6	340	-16.7	365	-18.0
316	11.4	341	-18.3		
317	9.5	342	-18.3		
318	4.8	343	-12.8		
319	4.8	344	-8.0		
320	-0.4	345	-10.2		
321	-0.4	346	-8.2		
322	0.9	347	-15.1		
323	-0.9	348	-7.6		
324	-2.8	349	-9.7		
325	-6.7	350	-8.5		

APPENDIX G

SAMPLE CALCULATIONS ON SIMULATION

G.1 Room simulation of energy consumption during the monitoring period

An excel spreadsheet, which was included as part of this research, was used in model validation. The input values needed was the building location, size of the room being simulated; construction materials of building components (i.e. walls, ceiling, and floor); number of pigs in the room and their average weight; room set-point temperature; outdoor air temperature; and equipment inventory, capacities, efficiencies and operations. The succeeding sections show the sample calculation for gestation room. The same calculations were used to determine the energy consumption for other areas of the barn.

G.1.1 Computation of heat transmission through building components

G.1.1.1 Room information and computation of U-value

Barn Name:	A	Type of Operation:	Farrow-Finish
Location:		Gestation Room size:	
latitude, deg	52.17	Length, m	57.5
longitude, deg	106.72	Width, m	15.2
		Ceiling height, m	3.66

Table G.1 Construction materials of building components (Barn A)

Materials		Conductivity, W/m-K	Specific heat, kJ/kg-K	Density, kg/m ³	Thickness, m	Thermal transmittance through conduction (h), W/m ² -K	Thermal resistance (R), m ² -K/W	Thermal transmittance (U), W/m ² -K
Floor	Soil	1.16	1.01	2,000	10.00		8.62	0.11
	Concrete	1.88	0.92	2,300	0.15		0.08	
Wall	h _o					22.70	0.04	0.05
	Prefinished metal	45.30	0.50	7,830	0.00042		0.00001	
	Fiberglass insulation						20.00	
	Fir plywood exterior grade	0.12	2.30	600	0.01		0.08	
	h _i					0.57	1.75	
Ceiling	h _i					0.32	3.13	0.03
	Fiberglass insulation						30.00	
	Fir plywood exterior grade	0.12	2.30	600	0.01		0.08	
Roof	Prefinished metal	45.30	0.50	7,830	0.00042		0.00001	0.04
	h _o					22.70	0.04	

Note: The thermal transmittance through convection for indoor (h_i) and outdoor (h_o) air film was computed in the subsequent sections. The construction materials of the major building components of other barns were relatively similar and were obtained from the blueprint of the barn.

Source: ASHRAE (2005)

The properties of construction materials were found in ASHRAE 2005 (Table 4, Chapter 25). The h_o value was taken from ASHRAE 2005 (Table 1 Chapter 25). Set-point temperature for gestation room during the monitoring period was 20°C. At that temperature, the kinematic viscosity (ν) is 15.11E-06 m²/s and air conductivity (λ_a) is 0.0257 W/m-k. The average air velocity (w) within the airspace was assumed to be 0.3 m/s as described in section 5.2.6.1. The h_i value was computed based on the following equation.

For wall:

$$Nu = 0.590 \left(\frac{wx}{\nu} \right)^{1/2} = 0.590 \left(\frac{0.3 \times 3.66}{15.11E-06} \right)^{1/2} = 159.04$$

$$h_i = \frac{Nu \cdot \lambda_a}{x} = \frac{159.04 \times 0.0257}{3.66} = 0.57$$

$$R_i = 1/0.57 = 1.75$$

For ceiling:

$$Nu = 0.590 \left(\frac{wx}{\nu} \right)^{1/2} = 0.590 \left(\frac{0.3 \times 15.2}{15.11E-06} \right)^{1/2} = 324.12$$

$$h_i = \frac{Nu \cdot \lambda_a}{x} = \frac{324.12 \times 0.0257}{15.2} = 0.32$$

$$R_i = 1/0.32 = 3.13$$

The total R-value per component was calculated using the following equation:

Example for wall component:

$$R = 0.04 + 0.00001 + 20 + 0.08 + 1.75 = 21.87$$

$$U = 1/R = 0.05$$

G.1.1.2 Sol-air temperature calculation

The calculation of heat transmission through the building components requires prior calculation for sol-air temperature. Sol-air temperature for Saskatoon in July for hour 14 (2 pm) was computed as follows:

- a) LST pertains to the local standard time in decimal hours. In this case, the LST was 14.
- b) Using ASHRAE 2005 (Chapter 31 Table 7), the equation of time (ET) in decimal minutes was -6.2 for July.
- c) The local standard time (LSM) meridian in decimal degree of arc was 90 for Central Standard Time.
- d) The local longitude (LON) in decimal degree of arc was 106.72.
- e) Apparent solar time (AST) in decimal hours was computed as follows:

$$\begin{aligned}AST &= LST + \frac{ET}{60} + \frac{(LSM - LON)}{15} \\ &= 14 + \frac{-6.2}{60} + \frac{(90 - 106.72)}{15} \\ &= 12.78\end{aligned}$$

- f) Hour angle in degrees was then computed as follows:

$$H = 15 (AST - 12) = 15 (12.78 - 12) = 11.7$$

- g) Solar altitude was computed based on the following equation:

$$\sin \beta = \cos L \cos \delta \cos H + \sin L \sin \delta$$

where: latitude (L) = 52.17; solar declination (δ) = 12.3 (ASHRAE 2005)

$$\begin{aligned}\beta &= \arcsin (\cos (52.17 * 3.14 / 180)) (\cos (12.3 * 3.14 / 180)) (\cos (11.7 * 3.14 / 180)) \\ &+ (\sin (52.17 * 3.14 / 180)) (\sin (12.3 * 3.14 / 180)) = 49\end{aligned}$$

- h) The solar azimuth in degrees was computed as follows:

$$\cos \phi = \frac{(\sin \beta \sin L - \sin \delta)}{(\cos \beta \cos L)}$$

$$\phi = \arccos \frac{(\sin (49 * 3.14 / 180)) (\sin (52.17 * 3.14 / 180)) - (\sin 12.3 * 3.14 / 180))}{(\cos (49 * 3.14 / 180)) (\cos (52.17 * 3.14 / 180))} - 17.6$$

- i) Surface azimuth (ψ) was 90° for west-facing walls.
 j) Surface-solar azimuth in degrees was calculated using the following equation.

$$\gamma = \phi - \psi = -17.6 - 90 = -107.6$$

- k) The surface tilt (Σ) from horizontal was 90° for vertical surface like walls.
 l) The incident angle in degrees was computed as follows:

$$\begin{aligned} \cos \theta &= \cos \beta \cos \gamma \sin \Sigma + \sin \beta \cos \Sigma \\ \theta &= \arccos (\cos (49 * 3.14 / 180) (\cos (-107.6 * 3.14 / 180)) (\sin (90 * 3.14 / 180)) \\ &+ (\sin (49 * 3.14 / 180)) (\cos (90 * 3.14 / 180)) = 101.46 \end{aligned}$$

- m) The direct normal irradiance (E_{DN}) was computed using the following expression:

$$E_{DN} = \left(\frac{A}{\exp (B / \sin \beta)} \right) CN = \left(\frac{20.6}{\exp (0.185 / (\sin (49 * 3.14 / 180)))} \right) 1.05 = 898.24$$

Values of A, B and CN are given in ASHRAE handbook 2005 chapter 31 and 33.

- n) The surface direct irradiance was computed as follows:

$$E_D = E_{DN} \cos \theta = 898.24 (\cos (101.46 * 3.14 / 180)) = -178.42$$

- o) Since $\cos \theta$ was greater than -0.20, the ratio Y of sky diffuse is equal to 0.45.

- p) The diffuse irradiance was then computed as follows:

$$E_d = C Y E_{DN} = 0.138 \times 0.45 \times 898.24 = 55.8$$

- q) The ground reflected irradiance was computed using the following equation:

$$\begin{aligned} E_r &= E_{DN} (C + \sin \beta) \rho_g (1 - \cos \Sigma) / 2 = 898.24 (0.138 \\ &+ (\sin (49 * 3.14 / 180)) 0.20 (1 - \cos 90)) = 79.85 \end{aligned}$$

r) The total surface irradiance was then computed as follows:

$$E_t = E_D + E_d + E_r = -178.42 + 55.8 + 79.85 = -42.79$$

s) The sol-air temperature in degree Celsius was computed using the following expression:

$$t_e = t_o + \frac{\alpha E_t}{h_o} - \frac{\varepsilon \Delta R}{h_o} = 21.4 + (0.052 \times -42.79) - 0 = 19.20^\circ\text{C}$$

The term, α / h_o , had a maximum value of 0.052 for dark colored surfaces.

G.1.1.3 Heat transmission through the external wall

Using the sol-air temperature computed for hour 14, the heat transmission through the external wall was computed using the following equation:

$$q_w = UA_s (t_e - t_i) = 0.05 \times (15.2 \times 3.66) \times (19.2 - 27.1) = -20.1 \text{ W}$$

A heat loss of 20.1 W through the west-facing external wall of the gestation room was computed at 2 pm on July 21. The same calculation was done for other times of the day. The heat transmission through internal walls was not considered because it was assumed that the adjacent room and hallway have relatively the same temperature with the room being simulated.

G.1.1.4 Heat transmission through the ceiling

The heat loss (indicated by the negative sign) through the ceiling was computed as 148.9 W for gestation room at hour 14.

$$q_c = UA_s (t_o - t_i) = 0.03 \times (15.2 \times 57.5) \times (27.1 - 21.4) = -148.9 \text{ W}$$

G.1.1.5 Perimeter heat loss

The heat loss coefficient (F) was taken from ASHRAE Chapter 29 for uninsulated slab floor. The perimeter heat loss was computed as 101 W for the gestation room at hour 14.

$$q_f = F \cdot P \cdot (t_o - t_i) = 1.17 \times 15.2 \times (21.4 - 27.1) = -101 \text{ W}$$

G.1.2 Computation of heat generated by pigs per room

Room type:	Gestation room
Number of pigs:	336 sows (obtained from barn records)
Average weight per pig (m):	265 kg (obtained from barn records)
Set-point temperature (t):	20°C (based on existing controller in the barn)

The total heat produced by pigs was computed using the following equation:

$$\begin{aligned} THP / kg &= 10^{[(1.189 - (0.005 * t)) - (0.345 * (\log m))]} \\ &= 10^{[(1.189 - (0.005 * 20)) - (0.345 * (\log 265))]} \\ &= 1.79 W / kg \end{aligned}$$

The total heat production in the room was computed as follows:

$$THP = 1.79 \times 265 \times 336 = 159,428 \text{ W}$$

The following table shows the total heat generated by pigs and the correction factor for animal activity for a 24-hour simulation. The animal activity correction factor was computed as follows:

Example for military hour (h) 3 am and h_{\min} was 2 am (Pedersen, 1996):

$$\begin{aligned} A &= 1 - a \sin \left[\left(\frac{2\pi}{24} \right) \times (h + 6 - h_{\min}) \right] \\ &= 1 - 0.20 \sin \left[\left(\frac{2\pi}{24} \right) \times (3 + 6 - 2) \right] \\ &= 0.807 \end{aligned}$$

The correction factor was applied to the total heat production and resulted to hourly total heat generated by the pigs. This heat along with other heat gain inside the building was the required heat to be removed through ventilation. This is also termed as the cooling load.

Table G.2 Hourly heat generated by pigs in gestation room

Hour	Total heat generated by pigs, W	Animal activity (diurnal correction factor)	Corrected total heat generated by pigs (total cooling load), W
1	159,428	0.807	128,635
2	159,428	0.800	127,543
3	159,428	0.807	128,621
4	159,428	0.827	131,798
5	159,428	0.858	136,855
6	159,428	0.900	143,449
7	159,428	0.948	151,131
8	159,428	1.000	159,377
9	159,428	1.051	167,628
10	159,428	1.100	175,320
11	159,428	1.141	181,930
12	159,428	1.173	187,008
13	159,428	1.193	190,209
14	159,428	1.200	191,314
15	159,428	1.193	190,248
16	159,428	1.173	187,084
17	159,428	1.142	182,038
18	159,428	1.101	175,452
19	159,428	1.052	167,775
20	159,428	1.001	159,530
21	159,428	0.949	151,278
22	159,428	0.901	143,581
23	159,428	0.859	136,963
24	159,428	0.827	131,874

Note: Values for all computations were done using a spreadsheet, which may vary due to rounding off.

G.1.3 Computation of heat generated by lights and feed motors

G.1.3.1 Lights

Number of fixtures: 48 (only 28 fixtures were in use during monitoring period, others need replacement)

Lamps/fixture: 2

Power rating: 34 W

Ballast factor: 95% (based on ASHRAE, 2005)

The total heat generated by the lights was computed as follows:

$$q_L = W F_u F_s = (34 \times 2 \times 28 \times 0.95) \times 1 \times 1.125 = 2,035 \text{ W}$$

The hourly heat generated by the lights was 2,035 W from hour 5 to hour 18 (5 am to 6 pm). On the other hand, the heat generated for hours 1-4 and hours 19-24 was zero since the lights were off during these times.

G.1.3.2 Feed motors

Number of motors:	5
Power rating:	0.5 hp (373 W)
Efficiency:	66% (as per manufacturer's specification found on the nameplate)
Hours of use:	20 minutes (data obtained from datalogger during monitoring period)
Time:	8 am and 3 pm (data obtained from datalogger during monitoring period)

$$q_m = (P_m / E_m) F_l F_u = \left(\frac{5 \times 373}{0.66} \right) \times 1 \times 20 / 60 = 942 \text{ W}$$

The hourly heat generated by the feed motors was 942 W from hour 8 to hour 15.

G.1.4 Computation of ventilation required in summer for gestation room

Using ventilation graph shown in Figure G.1, the ventilation rate for summer was determined for gestation room at different outdoor temperature. At hour 14, the outdoor temperature was 21.4°C and the ventilation rate required was 52,000 cfm. At this rate, all fan stages were running. Similar computations were done on each monitored room for the four barns.

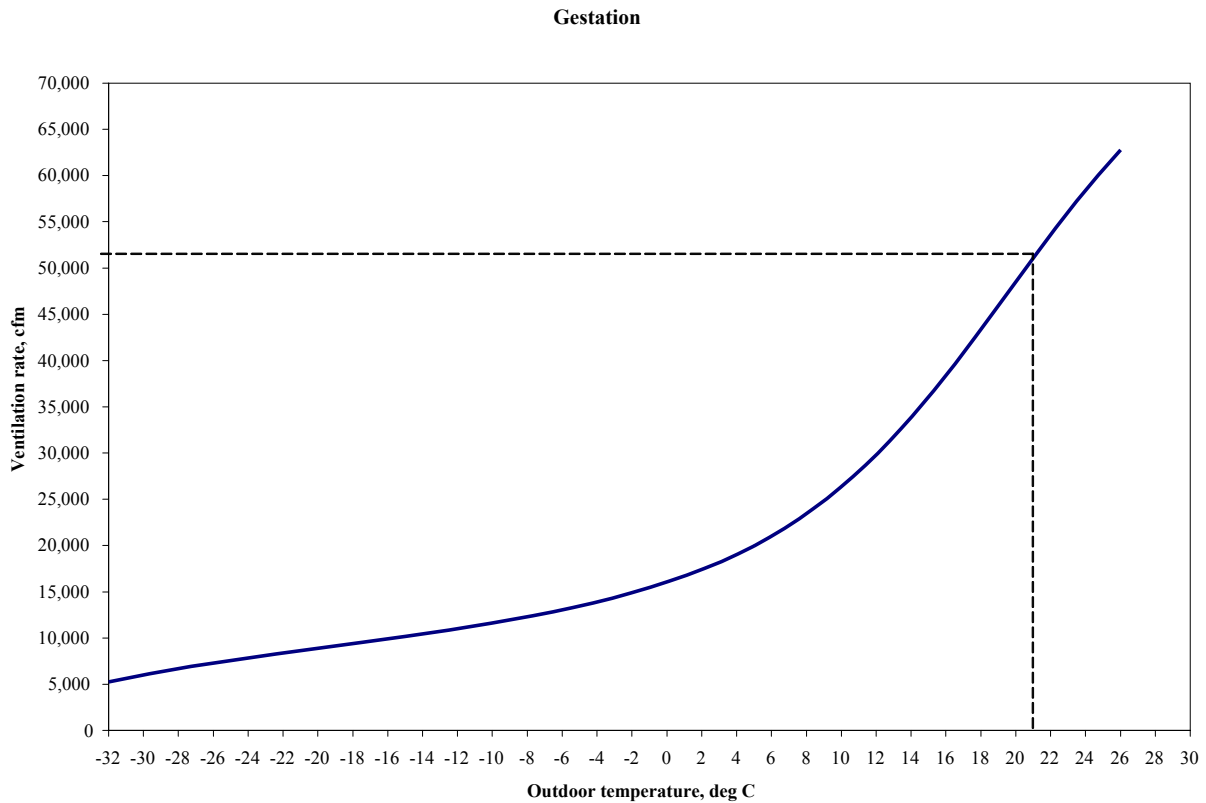


Figure G.1 Ventilation graph for gestation room

The electrical energy consumption was then computed based on the operation of the fans per hour using the fan efficiency in cfm/W. In this case, all fans were running to remove the heat generated by the sows. The following table shows the fan data which were used to determine the energy consumption at hour 14. The information on fan models, capacity, and efficiency was obtained from the manufacturer’s specification.

Table G.3 Fan Specifications

	Fan Model		
	TR12	TR24	TR36
Quantity	2	3	3
Capacity, cfm	1,936	6,704	12,653
Efficiency, cfm/W	7.5	11.4	14.8

A sample calculation for electrical energy consumption at hour 14 was done using the following equation:

$$E_F = ((1936 \text{ cfm} * 2*1\text{hr}) / 7.5 \text{ cfm/W})/1000 = 0.52 \text{ kWh (TR 12 fans)}$$

$$E_F = ((6704 \text{ cfm} * 3*1\text{hr}) / 7.5 \text{ cfm/W})/1000 = 1.76 \text{ kWh (TR 24 fans)}$$

$$E_F = ((12653 \text{ cfm} * 3*1\text{hr}) / 7.5 \text{ cfm/W})/1000 = 2.57 \text{ kWh (TR 36 fans)}$$

A total of 4.85 kWh was consumed by all the fans running in full capacity at 2 pm. Furthermore, all fans are continuously running in gestation room for the 24-hr simulation. Thus, the total consumption for 24 hours in gestation room was 116.3 kWh. The measured average daily electrical energy consumption of the fans was 123.3 kWh/day. The percent difference computed was 5.86%.

G.1.5 Computation of supplemental heat required in winter

The heat transmission for the building components, pigs, lights and feed motors were computed using the same previous expressions used in summer. The ventilation rate was based on the ventilation graph developed (as described in section 5.2.11.1). For the 24-hour period, the outside temperature ranged from -21 to -26°C. In this case, constant minimum ventilation and supplemental heat were required. At stage 1, the ventilation rate would be 3872 cfm (1828 L/s). This was based on the actual measurement done during the monitoring period. The electrical energy consumed by these fans using previous equations was 15.92 kWh for the 24-hr simulation at the set-point temperature (t_i) of 18°C. The density of air is 1.2 while the specific heat of air was 1.02. The heat loss through ventilation fans at hour 14 was computed as follows:

$$q_F = \rho V C_p (t_o - t_i) = 1.2 \times 1828 \times 1.02 (-21.8 - 18) = -89,031 \text{ W}$$

The supplemental heat required at hour 14 was computed using the data previously computed for each heat gain/loss and expressed in the following expression:

$$q_H = (q_P + q_L + q_M) - (q_F + q_B) = (191,314 + 2035 + 0) - (89,031 + 270) = 104,048 \text{ W}$$

The heating loads for other hours of the day were computed using the same equation and the supplemental heat was required only at hour 24. This resulted to -0.898 kWh/day during the 24-hr simulation, which was converted to MJ/m³ by multiplying factor 3.6. The fuel consumption was then determined using the following equation:

$$F_h = \frac{\{[(q_F + q_B) - (q_P + q_L + q_M)]/t\} * 3.6}{\eta HV} = \frac{(0.898 \text{ kWh/day} \times 3.6 \text{ MJ/kWh})}{0.70 \times 37.2 \text{ MJ/m}^3} = 0.124 \text{ m}^3 / \text{day}$$

The heater efficiency was 70% (heater's specifications) and heating value of natural gas for December 2007 at the barn location was 37.2 MJ/m³ (SaskEnergy, 2008). The fuel consumption was 0.124 m³ and the energy consumption was 3.2 MJ. The average actual gas consumed during the monitoring period was 0.10 m³/day and the energy consumption was 2.6 MJ.

The percent difference between simulated and actual gas consumption was computed using the following expression:

$$\% \text{ difference} = \frac{|3.2 \text{ MJ} - 2.6 \text{ MJ}|}{\frac{3.2 \text{ MJ} + 2.6 \text{ MJ}}{2}} * 100 = 20.41\%$$

G.2 Sample calculation for simulating the electrical energy consumption of the exhaust fan

G.2.1 Heat transmission through building components

The heat transmission through the external walls, floor perimeter, and ceiling/roof was computed using equations 5.7 to 5.16. Thermal transmittance (U-value) of each building component was previously determined in Table G.1. Table G.4 shows the summary of thermal transmittance (UA-value) for each building component in the farrowing room.

Table G.4 Calculated UA-value for farrowing room

Building Construction:	U-value	Farrowing Room			UA VALUE
		Length, m	Width, m	Height, m	
Floor	0.115		7.16		0.82
Wall	0.047		7.16	3.66	1.23
Ceiling/Roof	0.031	12.8	7.16		2.83

G.2.2 Heat generated by the pigs

The heat generated by the pigs was computed using equations 5.3 and 5.4. An hourly average of heat generated by pigs was determined. Table G.5 show the information required by the spreadsheet and Table G.6 shows the heat generated by pigs in the farrowing room.

Table G.5 Information required in the calculation of heat generated by pigs

Information	Value
Number of pigs:	12
Set-point temp:	24
Average Weight per pig, kg:	215
THP per pig,(W/kg):	1.84
Total Heat Production per room, W:	4,742

Table G.6 Heat generated by pigs in the farrowing room

Hour	Total heat production (100%)	Animal activity (diurnal correction factor)	Total Cooling Load
1	4,742	0.807	3,826
2	4,742	0.800	3,793
3	4,742	0.807	3,825
4	4,742	0.827	3,920
5	4,742	0.858	4,070
6	4,742	0.900	4,266
7	4,742	0.948	4,495
8	4,742	1.000	4,740
9	4,742	1.051	4,986
10	4,742	1.100	5,214
11	4,742	1.141	5,411
12	4,742	1.173	5,562
13	4,742	1.193	5,657
14	4,742	1.200	5,690
15	4,742	1.193	5,658
16	4,742	1.173	5,564
17	4,742	1.142	5,414
18	4,742	1.101	5,218
19	4,742	1.052	4,990
20	4,742	1.001	4,745
21	4,742	0.949	4,499
22	4,742	0.901	4,270
23	4,742	0.859	4,073
24	4,742	0.827	3,922
Hourly average heat generated by pigs per day			4,742 W

G.2.3 Heat gain from lights, heat pads and heat lamps

The heat gain from lights, heat pad, and heat lamps in the farrowing room as shown in Tables G.7, G.8 and G.9 were determined by converting electrical power to heat gain.

Table G.7 Heat gain from lights in the farrowing room

Information	Value
Number of lamps/fixture:	2
Number of fixture:	10
Total number of lamps:	20
Power rating, W	34
Lighting use factor:	1
Special allowance factor:	1.13
Lights ON:	7:00:00 AM
Lights OFF:	2:00:00 PM
Hours of use:	8
Hourly average heat gain from lights:	256

Table G.8 Heat gain from heat pads in the farrowing room

Information	Value
Number of pads	8
Power rating, W	169
Hours of use per day	24
Number of farrowing times per year	24
Number of days in use per year	336
Hourly average heat gain from lights per day	1,352

Table G.9 Heat gain from heat lamps in the farrowing room

Information	Value
Number of lamps	16
Power rating, W	175
Hours of use per day (only for 3 days)	24
Number of farrowing times per year	24
Number of days in use per year	72
Hourly average heat gain from lights per day	2,800

G.2.3 Development of Ventilation Graph

The minimum and maximum ventilation rate was computed using heat balance for all types of rooms. The data required to create the ventilation graph was based on the previous calculated data on heat gains and losses. The design condition for summer and winter was obtained from ASHRAE (2005). The indoor temperature used to calculate the minimum ventilation for winter was the set-point temperature in the farrowing room. On the other hand, the indoor temperature used to calculate the maximum temperature for summer was the temperature which would activate all fan stages. This information was obtained from the ventilation design of the barn. This information also corresponds to the upper limit of thermoneutral zone (Renaudeau et al., 2006). A sample calculation for farrowing room with stages 1 and 2 fans are shown in the succeeding sections. Table G.10 shows the information required to determine the maximum and minimum ventilation rate and Figure G.2 shows the ventilation graph.

Table G.10 Calculated data for determining minimum and maximum ventilation rate

Information	Value
Building data (Source: Blue print and ASHRAE, 2005):	
1) UA value (wall)	1.23
2) Perimeter factor multiplied by floor perimeter	62.29
3) UA value (ceiling)	2.83
Indoor design Condition:	
1) Indoor set-point temp, deg C (winter)	24
2) Temp control setting for activating all fan stages, deg C (summer)	28.5
Outside design Condition (Source: ASHRAE, 2005)	
1) Outdoor temp, deg C (Saskatoon, winter)	-32
2) Outdoor temp, deg C (Saskatoon, summer)*	26
Animal data:	
1) Hourly average heat generated by pigs per day	4,742
Equipment data:	
1) Hourly average heat gain from light per day, W	256
2) Hourly average heat gain from motor per day, W	0.0
3) Hourly average heat gain from heat lamp per day, W	2800
4) Hourly average heat gain from heat pad per day, W	1352
Computed ventilation rate:	
Minimum Ventilation Rate, cfm/room (based on temperature control)	170
Minimum Ventilation Rate, cfm/room (intersection of temperature control and moisture control curve)	250
Maximum Ventilation Rate, cfm/room	6,307

* Design conditions for summer ventilation was for warm weather not hottest temperature recorded (Albright, 1990)

The minimum and maximum ventilation rate for temperature control was computed as follows using the information in Table G.10. The minimum ventilation was computed using the room set-point temperature (t_i) and the design extreme condition at 99% (ASHRAE, 2005) for Saskatoon of -32°C (t_o)

Temperature control:

$$V_f \text{ (minimum)} = \frac{q_P + q_L + q_{HL} + q_{HP} - q_b}{1006 \rho_{air} (t_i - t_o)} \times 2118 = \frac{q_P + q_L + q_{HL} + q_{HP} - UA(t_i - t_o)}{\rho_{air} (t_i - t_o)} \times 2.11$$

$$= \frac{4742 + 256 + 2800 + 1352 - 66.35(24 - (-32))}{1.2 * (24 - (-32)) * 60 \text{sec} / (0.3048 \text{m}^3 / \text{ft}^3)} \times 2.11 = 170 \text{ cfm}$$

Moisture control:

The moisture production was determined using the following expression (Li, 2000) and was converted to kg/s.

$$\log \overline{M}_n = -1.4147 + 0.00539W + 0.00171T - 0.0000579W \cdot T - 0.0000141W^2 + 0.000446T^2$$

$$\text{Moisture production} = \{10^{(-1.4147 + (0.00539*B6) + (0.00171*B5) - (0.0000579*B6*B5) - (0.0000141*B6*B6) + (0.000446*B5*B5))}\} * 12/3600 = 0.000411 \text{ kg/s}$$

The ventilation rate to remove moisture at different outdoor temperature was then computed using the following expression. The humidity ratio (W_o) at 80% relative humidity for different outdoor temperature is shown in Table G.11.

$$V_f = \frac{\text{Moisture production}}{\rho_{air} (0.006076 - W_o)}$$

The calculation of ventilation rate required to remove moisture at outdoor temperature of -25 was determined as follows:

$$V_f = \frac{\text{Moisture production}}{\rho_{air} (0.006076 - W_o)} = \frac{0.000411 \text{ kg/s}}{1.2 * (0.006076 - 0.000353)} = 0.0598 \text{ m}^3 / \text{s or } 127 \text{ cfm}$$

The ventilation curve for moisture control was then generated at different outdoor temperature as shown in Figure G.1.

Table G.11 Humidity ratio for different outdoor temperature

Outdoor temperature, °C	Humidity ratio @80% RH, kg/kg
-25	0.000353
-20	0.000577
-15	0.000925
-10	0.001457
-5	0.002256
0	0.003441
5	0.004924

The maximum ventilation was computed using design indoor temperature (t_i) of 28.5°C and the design condition at 2% (ASHRAE, 2005) for Saskatoon of 26°C (t_o). The chosen inside temperature was based on the biological needs of the pigs. The highest stage of ventilation would be activated at the temperature where heat stress could affect production (Albright, 1990), thus, the temperature set to activate all fan stages in farrowing room was selected as the design indoor temperature. This information was obtained from the ventilation design of farrowing room in Barn A.

$$V_f (\text{maximum}) = \frac{q_P + q_L + q_{HL} + q_{HP} - q_b}{1006 \rho_{air} (t_i - t_o)} \times 2118 = \frac{q_P + q_L + q_{HL} + q_{HP} - UA(t_i - t_o)}{\rho_{air} (t_i - t_o)} \times 2.11$$

$$= \frac{4742 + 256 + 2800 + 1352 - 66.35(28.5 - (26))}{1.2 * (28.5 - (26)) * 60 \text{ sec} / (0.3048 \text{ m}^3 / \text{ft}^3)} \times 2.11 = 6307 \text{ cfm}$$

Farrowing Room

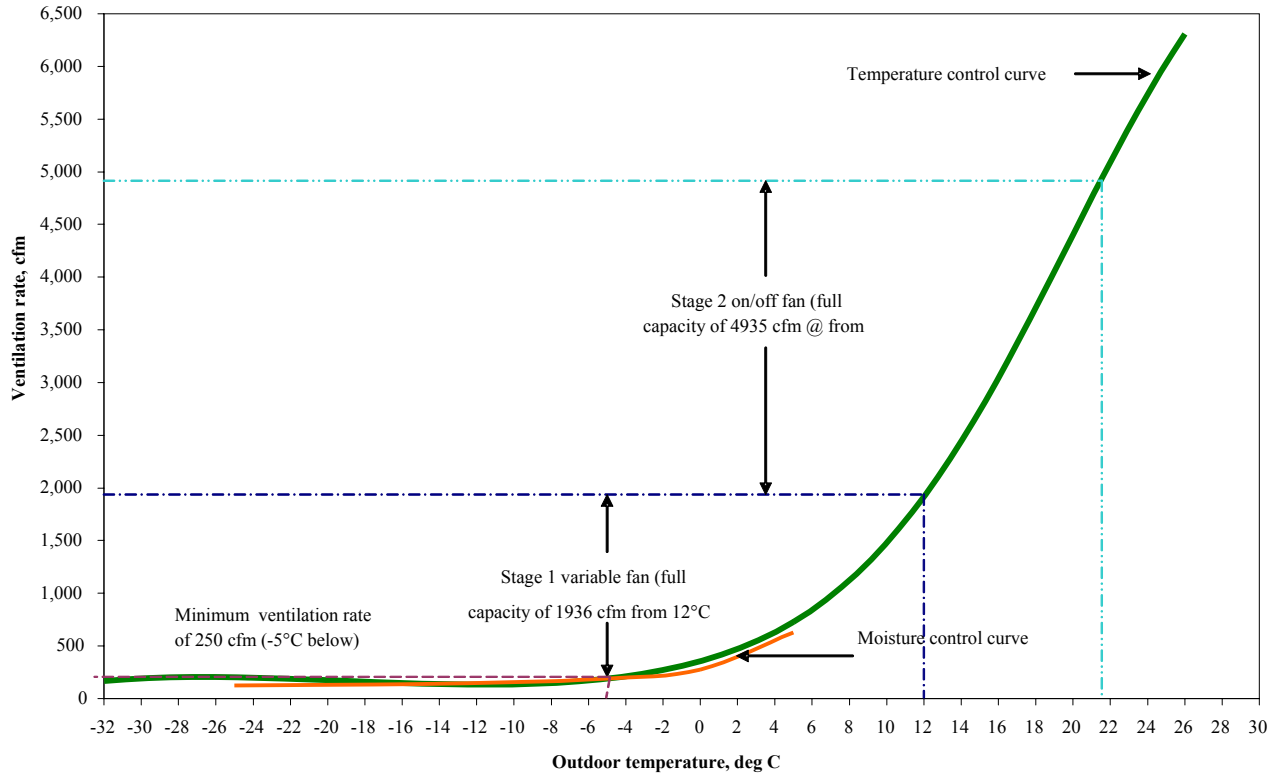


Figure G.2 Ventilation graph for farrowing room

The ventilation graph shows that the minimum ventilation rate for winter was 250 cfm for outdoor temperatures below -5°C. Above that temperature, the stage 1 fan with a capacity of 1936 cfm would be activated. When outdoor temperature is above 12°C, stage 2 fan with a capacity of 4935 would be activated. Using this relationship, the ventilation rate can be computed at different outdoor temperatures. The ventilation rate for days 100 to 109 ventilation graph is shown in Table G.12. Since the outside temperature is above -5°C but below 12 °C for day 100, the stage 1 fan with a capacity of 1936 cfm would be activated. For day 103, the stages 1 & 2 fan would be activated since the outdoor temperature is above 12°C.

Table G. 12 Ventilation required at different outside temperature using ventilation graph

Day	Outside temperature, °C	Required ventilation, cfm/hour/day
100	2.6	1,936
101	1.5	1,936
102	11.4	1,936
103	16.9	1,936 + 4,935 = 6,871
104	21.9	6,871
105	13.9	6,871
106	17.0	6,871
107	19.2	6,871
108	18.0	6,871
109	20.5	6,871

The electrical energy consumption for the fans was then computed using the fan capacity and efficiency. For day 100, the electrical energy consumption of the fan was computed as 0.258 kWh using the following expression:

$$E_f = \frac{\text{fan capacity}}{\text{fan efficiency}} \times \text{hours of use} = \frac{1936 \text{ cfm}}{7.5 \text{ cfm/W}} * \frac{1 \text{ hour}}{1000 \text{ W/kW}} = 0.258 \text{ kWh}$$

The simulated annual electrical energy consumption of the exhaust fans for farrowing room was determined using equation 5.24 and ventilation graph over the 365-day data obtained from weather station (Appendix F). The same computation was done for other areas in the barn.

G.3 Simulation of the annual energy consumption for the entire production area: baseline case

The annual energy consumption of different types of equipment in farrowing, nursery, grow-finish, and gestation rooms for Barn A are shown in Table G.14. A spreadsheet was used to compute for the energy consumption and is included as part of this thesis.

Table G.14 Annual energy consumption in Barn A for different types of equipment

Equipment	Farrowing		Nursery		Grow-Finish		Gestation		Total kWh per year for entire production area
	kWh per day per room	kWh per year for 8 rooms	kWh per day per room	kWh per year for 8 rooms	kWh per day per room	kWh per year for 14 rooms	kWh per day per room	kWh per year for 2 rooms	
Lighting system : 34 W T-12 fluorescent	5.4	15,768	5.4	15,768	6.5	33,215	45.7	33,361	98,112
Creep heating system: Combination of heat lamp 175 W and heat pad 169 W									121,774
a. Heat lamps, kWh (3 days per farrowing)	67.2	38,707							
b. Heat pads, kWh (24-h continuous operation for 2 weeks per farrowing)	32.4	83,067							
Recirculation Fan: With 7.5 cfm/W	3.84	11,213	3.84	11,213	8.51	43,479	25.53	18,634	84,539
Exhaust Fans: Baseline design: Feed motor (0.5 hp @70% efficiency)		37,135		50,975		285,69		61,514	435,323
Manual feeding				2,668		6,671		1,429	10,769

Note: Farrowing times was approximately 24 times per room per year. There were a total of 8 feed motors in nursery, 28 in grow-finish, and 10 in gestation rooms. Feed motors in nursery, grow-finish, and gestation rooms were used 3.5 hours, 2.5 hours, and 1.5 hours on the average, respectively.

The annual electrical energy consumption for equipment (i.e. lights, heat pads, heat lamps, recirculation fan and feed motors) were determined using equations 5.18-5.22. Sample calculations

Baseline Case for lighting system (using equation 5.18):

Farrowing Room:

$$= [(34 \text{ W} * 20 \text{ lamps})/1000] * 8 \text{ hours} * 8 \text{ rooms} * 365 \text{ days} = 15,768 \text{ kWh/yr}$$

Nursery Room:

$$= [(34 \text{ W} * 20 \text{ lamps})/1000] * 8 \text{ hours} * 8 \text{ rooms} * 365 \text{ days} = 15,768 \text{ kWh/yr}$$

Grow-Finish Room:

$$= [(34 \text{ W} * 24 \text{ lamps})/1000] * 8 \text{ hours} * 14 \text{ rooms} * 365 \text{ days} = 33,215 \text{ kWh/yr}$$

Gestation Room:

$$= [(34 \text{ W} * 96 \text{ lamps})/1000] * 14 \text{ hours} * 2 \text{ rooms} * 365 \text{ days} = 33,361 \text{ kWh/yr}$$

Whole barn:

$$\begin{aligned} &= (15,768 \text{ kWh/yr}) + (15,768 \text{ kWh/yr}) + (33,215 \text{ kWh/yr}) + (33,361 \text{ kWh/yr}) \\ &= 98,112 \text{ kWh/yr} \end{aligned}$$

Baseline Case for creep heating system in farrowing room (using equations 5.19 and 5.20):

$$\text{Heat lamp} = [(175 \text{ W} * 16 \text{ lamps})/1000] * 24 \text{ hours} * 8 \text{ rooms} * 72 \text{ days} = 38,707 \text{ kWh/yr}$$

$$\text{Heat pad} = [(169 \text{ W} * 8 \text{ pads})/1000] * 24 \text{ hours} * 8 \text{ rooms} * 320 \text{ days} = 83,067 \text{ kWh/yr}$$

$$\text{TOTAL} = (38,707 \text{ kWh/yr}) + (83,067 \text{ kWh/yr}) = 121,774 \text{ kWh/yr}$$

Baseline Case for recirculation fan (using equation 5.21):

Farrowing Room:

$$\begin{aligned} &= [(600 \text{ cfm} / 7.5 \text{ cfm per W} * 2 \text{ fans})/1000] * 24 \text{ hours} * 8 \text{ rooms} * 365 \text{ days} \\ &= 11,213 \text{ kWh/yr} \end{aligned}$$

Nursery Room:

$$\begin{aligned} &= [(600 \text{ cfm} / 7.5 \text{ cfm per W} * 2 \text{ fans})/1000] * 24 \text{ hours} * 8 \text{ rooms} * 365 \text{ days} \\ &= 11,213 \text{ kWh/yr} \end{aligned}$$

Grow-Finish Room:

$$\begin{aligned} &= [(3,368 \text{ cfm} / 9.5 \text{ cfm per W} * 1 \text{ fans})/1000] * 24 \text{ hours} * 14 \text{ rooms} * 365 \text{ days} \\ &= 43,479 \text{ kWh/yr} \end{aligned}$$

Gestation Room:

$$\begin{aligned} &= [(3,368 \text{ cfm} / 9.5 \text{ cfm per W} * 3 \text{ fans})/1000] * 24 \text{ hours} * 2 \text{ rooms} * 365 \text{ days} \\ &= 18,634 \text{ kWh/yr} \end{aligned}$$

Whole barn:

$$\begin{aligned} &= (11,213 \text{ kWh/yr}) + (11,213 \text{ kWh/yr}) + (43,479 \text{ kWh/yr}) + (18,634 \text{ kWh/yr}) \\ &= 84,539 \text{ kWh/yr} \end{aligned}$$

Baseline Case for exhaust fan (using ventilation graph discussed in section G.2):

The development of ventilation graph was discussed in section G.2 with sample calculation on the farrowing room. The same calculations were done for other areas in the barn and a spreadsheet was used to implement the mathematical model.

Farrowing Room: 37,135 kWh/yr

Nursery Room: 50,975 kWh/yr

Grow-Finish Room: 285,699 kWh/yr

Gestation Room: 61,514 kWh/yr

$$\begin{aligned} \text{Whole barn:} &= (37,135 \text{ kWh/yr}) + (50,975 \text{ kWh/yr}) + (285,699 \text{ kWh/yr}) \\ &+ (61,514 \text{ kWh/yr}) = 435,323 \text{ kWh/yr} \end{aligned}$$

Baseline Case for feed motor (using equation 5.22):

Nursery Room:

$$\begin{aligned} &= [(0.5 \text{ hp} * 0.7 \text{ efficiency} * 0.746 \text{ kW/hp} * 8 \text{ motors})] * 3.5 \text{ hours} * 365 \text{ days} \\ &= 2,668 \text{ kWh/yr} \end{aligned}$$

Grow-Finish Room:

$$\begin{aligned} &= [(0.5 \text{ hp} * 0.7 \text{ efficiency} * 0.746 \text{ kW/hp} * 28 \text{ motors})] * 2.5 \text{ hours} * 365 \text{ days} \\ &= 6,671 \text{ kWh/yr} \end{aligned}$$

Gestation Room:

$$\begin{aligned} &= [(0.5 \text{ hp} * 0.7 \text{ efficiency} * 0.746 \text{ kW/hp} * 10 \text{ motors})] * 1.5 \text{ hours} * 365 \text{ days} \\ &= 1,429 \text{ kWh/yr} \end{aligned}$$

Whole barn:

$$\begin{aligned} &= (2,668 \text{ kWh/yr}) + (6,671 \text{ kWh/yr}) + (1,429 \text{ kWh/yr}) \\ &= 10,769 \text{ kWh/yr} \end{aligned}$$

G.4 Simulation of annual energy savings for the entire production area: Using energy efficient lights to the baseline case

Table G.14 shows the annual energy savings using option 3 in Chapter 5 (25-W T8 lamps). The baseline case for barn A is a 34-W T12 lamp. Using equation 5.18, the electrical energy consumption of lights was computed. The following shows the sample calculation to determine the annual energy savings associated with using 25-W T8 lamp. The baseline case for lighting was computed in the previous section (G.3).

Table G.14 Annual energy savings on the application of lower wattage higher lumen lighting system to the baseline case

	Farrowing		Nursery		Grow-Finish		Gestation		Whole barn		Annual Savings	
	Baseline Case	Option 3	Baseline Case	Option 3	Baseline Case	Option 3	Baseline Case	Option 3	Baseline Case	Option 3	kWh	\$ (@\$0.0938 per kWh)
kWh/day per room	5.4	4.0	5.4	4.0	6.5	4.8	45.7	32.2				
# of rooms		8		8		14		2				
# of days per year		365		365		365		365				
Total, kWh/yr	15,768	11,680	15,768	11,680	33,215	24,528	33,361	23,506	98,112	71,394	26,718	\$ 2,506.15

Option 3:

Farrowing Room: = $[(25 \text{ W} * 20 \text{ lamps})/1000] * 8 \text{ hours} * 8 \text{ rooms} * 365 \text{ days} = 11,680 \text{ kWh/yr}$

Nursery Room: = $[(25 \text{ W} * 20 \text{ lamps})/1000] * 8 \text{ hours} * 8 \text{ rooms} * 365 \text{ days} = 11,680 \text{ kWh/yr}$

Grow-Finish Room: = $[(25 \text{ W} * 24 \text{ lamps})/1000] * 8 \text{ hours} * 14 \text{ rooms} * 365 \text{ days}$
= 24,528 kWh/yr

Gestation Room: = $[(25 \text{ W} * 92 \text{ lamps})/1000] * 14 \text{ hours} * 2 \text{ rooms} * 365 \text{ days} = 23,506 \text{ kWh/yr}$

Whole barn: = $(11,680 \text{ kWh/yr}) + (11,680 \text{ kWh/yr}) + (24,528 \text{ kWh/yr}) + (23,506 \text{ kWh/yr})$
= 71,394 kWh/yr

Energy Savings:

Whole barn: = $(98,112 \text{ kWh/yr}) - (71,394 \text{ kWh/yr}) = 26,718 \text{ kWh/yr}$
= $26,718 \text{ kWh/yr} * \$0.0938/\text{kWh} = \$2,506.15$

APPENDIX H

ELECTRICAL ENERGY CONSUMPTION OF EXHAUST FAN USING VENTILATION GRAPH AND ACTUAL INSIDE TEMPERATURE

The electrical energy consumption of exhaust fans were computed and discussed in detail in section G.2. Table H.1 shows the computation of the electrical energy consumption per day using the ventilation graph developed while Table H.2 shows the energy consumption using the actual inside temperature. A spreadsheet was used to implement the mathematical model and is included as part of this thesis. The sample computation on electrical energy consumption of exhaust fans in farrowing room using two different methods is expressed as follows:

Method 1: Using the ventilation graph

At time 14 (2 pm), the outside temperature was 24.2°C. Using the ventilation graph shown in section G.2, when outdoor temperature is above 12 °C, stage 1 and 2 fans will be activated. Thus, at 2 pm, the electrical energy consumption was 0.752 kWh. The electrical requirement for each fan was computed as follows:

Stage 1 fan:

$$E_f = \frac{\text{fan capacity}}{\text{fan efficiency}} \times \text{hours of use} = \frac{1936 \text{ cfm}}{7.5 \text{ cfm/W}} * \frac{1 \text{ hour}}{1000 \text{ W/kW}} = 0.258 \text{ kWh}$$

Stage 2 fan:

$$E_f = \frac{\text{fan capacity}}{\text{fan efficiency}} \times \text{hours of use} = \frac{4935 \text{ cfm}}{10.0 \text{ cfm/W}} * \frac{1 \text{ hour}}{1000 \text{ W/kW}} = 0.494 \text{ kWh}$$

Table H.1 Electrical energy consumption of exhaust fans for 24 hours in farrowing room using ventilation graph

Hour	Outside temperature, °C	CFM required (cfm/hour/day)	Stage 1 fan ON? (kWh)	Stage 2 fan ON? (kWh)	Average FAN kWh/hour/day
1	14.4	4,935	0.258	0.494	0.752
2	11.8	1,936	0.258	0.000	0.258
3	12.7	4,935	0.258	0.494	0.752
4	10.8	1,936	0.258	0.000	0.258
5	10.3	1,936	0.258	0.000	0.258
6	9.8	1,936	0.258	0.000	0.258
7	10.1	1,936	0.258	0.000	0.258
8	12.9	4,935	0.258	0.494	0.752
9	15.7	4,935	0.258	0.494	0.752
10	18.4	4,935	0.258	0.494	0.752
11	20.2	4,935	0.258	0.494	0.752
12	21.4	4,935	0.258	0.494	0.752
13	23.6	4,935	0.258	0.494	0.752
14	24.2	4,935	0.258	0.494	0.752
15	24.8	4,935	0.258	0.494	0.752
16	25.6	4,935	0.258	0.494	0.752
17	25.2	4,935	0.258	0.494	0.752
18	25.8	4,935	0.258	0.494	0.752
19	25.8	4,935	0.258	0.494	0.752
20	24.9	4,935	0.258	0.494	0.752
21	23.7	4,935	0.258	0.494	0.752
22	22.1	4,935	0.258	0.494	0.752
23	18.8	4,935	0.258	0.494	0.752
24	18.4	4,935	0.258	0.494	0.752
				TOTAL	15.57

Method 2: Using actual inside temperature

At time 14 (2 pm), the outside temperature was 24.2°C. The net heat gain was 8,078 W. The net heat gain was computed using the heat balance discussed in section G.1. Using the following equation, ventilation rate required at 2 pm was:

$$V_f = \frac{q_{net}}{1006 \rho_{air} (t_i - t_o)} \times 2118 = \frac{8,028}{1006 * 1.2 (26.39 - 24.2)} * 2118 = 6,434 \text{ cfm}$$

The value 2,118 is a conversion factor from m³/s to cfm, thus, small differences in values computed can be observed because the mathematical model was implemented using a spreadsheet.

Table H.2 Electrical energy consumption of exhaust fans for 24 hours in farrowing room using actual inside temperature measured during monitoring

HOUR	Outside temperature, °C	Inside Temperature, °C	Net Heat Gain, W	cfm required to ventilate space	if greater than 1936 (max 6871 cfm), 2 stages (1-2) fans are running: =1936+4935	if less than 1936 cfm, only one stage(1) fans are running: =1936	TOTAL, FAN kWh
1	14.4	19.71	5,952	1,967	0.494	0.258	0.75
2	11.8	17.50	6,290	1,937	0.494	0.258	0.75
3	12.7	17.19	6,051	2,365	0.494	0.258	0.75
4	10.8	16.89	6,799	1,958	0.494	0.258	0.75
5	10.3	16.91	7,250	1,924	0.494	0.258	0.75
6	9.8	16.91	7,324	1,808	0.494	0.258	0.75
7	10.1	17.96	7,625	1,703	0.494	0.258	0.75
8	12.9	18.23	7,078	2,329	0.494	0.258	0.75
9	15.7	20.11	7,324	2,912	0.494	0.258	0.75
10	18.4	21.14	7,552	4,846	0.494	0.258	0.75
11	20.2	22.68	7,749	5,482	0.494	0.258	0.75
12	21.4	24.27	7,900	4,829	0.494	0.258	0.75
13	23.6	25.54	7,995	7,242	0.494	0.258	0.75
14	24.2	26.39	8,028	6,434	0.494	0.258	0.75
15	24.8	27.09	7,384	5,666	0.494	0.258	0.75
16	25.6	27.37	6,240	6,203	0.494	0.258	0.75
17	25.2	27.62	6,090	4,409	0.494	0.258	0.75
18	25.8	27.67	5,894	5,522	0.494	0.258	0.75
19	25.8	27.36	5,666	6,384	0.494	0.258	0.75
20	24.9	26.66	5,421	5,421	0.494	0.258	0.75
21	23.7	24.87	5,175	7,777	0.494	0.258	0.75
22	22.1	23.65	4,946	5,601	0.494	0.258	0.75
23	18.8	21.20	4,749	3,475	0.494	0.258	0.75
24	18.4	20.59	5,952	3,132	0.494	0.258	0.75
TOTAL							16.6

APPENDIX I

VARIOUS LIGHTING OPTIONS USED IN BUILDING SIMULATION

Table I.1 Lumen per watt ratings of different lighting options

Lighting Options	Farrowing	Nursery	Grow-Finish	Gestation
1. Lights specs (F34T12) (2,183 lumen/lamp)				
Rating, W	34	34	34	34
# of fixtures	10	10	12	48
Lamp/fixture	2	2	2	2
Hours of use per day	8	8	8	14
Lumen/W	64.2	64.2	64.2	64.2
Total Lumens per room	43,656	43,656	52,387	209,549
2. Lights specs (F32T8) - lower wattage higher lumens (2,592 lumen/lamp)				
Rating, W	32	32	32	32
# of fixtures	9	9	10	41
Lamp/fixture	2	2	2	2
Hours of use per day	8	8	8	14
Lumen/W	81	81	81	81
Total Lumens per room	51,840	51,840	62,208	248,832
3. Lights specs (F25T8) - lower wattage higher lumens (2,280 lumen/lamp)				
Rating, W	25	25	25	25
# of fixtures	10	10	12	46
Lamp/fixture	2	2	2	2
Hours of use per day	8	8	8	14
Lumen/W	91	91	91	91
Total Lumens per room (T8)	45,600	45,600	54,720	218,880
4. Lights specs (F28T5) - lower wattage higher lumens (2,912 lumen/lamp)				
Rating, W	28	28	28	28
# of fixtures	8	8	9	36
Lamp/fixture	2	2	2	2
Hours of use per day	8	8	8	14
Lumen/W	104	104	104	104
Total Lumens per room	58,240	58,240	69,888	279,552
5. Lights specs (F24T5HO) - lower wattage higher lumens (2,064 lumen/lamp)				
Rating, W	24	24	24	24
# of fixtures	12	12	14	52
Lamp/fixture	2	2	2	2
Hours of use per day	8	8	8	14
Lumen/W	86	86	86	86
Total Lumens per room	41,280	41,280	49,536	198,144

Sample Calculation:

For farrowing room, total lumens for option 2 were 51,840 lumens (T8) and 43,656 lumens (T12). The 2 T8 lamps can be reduced from the existing 20 T12 lamps. This was determined using the following equation:

Number of lamps that can be reduced from existing 20 T12 lamp = $(51,840 - 43,656 / 2952) = 3$ lamps. However, there were 2 lamps per fixture, therefore; only 2 lamps can be reduced.

APPENDIX J

SENSITIVITY ANALYSIS ON HEAT EXCHANGER

Effectiveness of the heat exchanger greatly affects how much savings can be realized. Thus, a sensitivity analysis was done to see quantify the effect of varying effectiveness. The heat exchanger has effectiveness ranging from 0.45 to 0.70. The minimum (0.45), maximum (0.70), and the average (0.60) values were used. Table I.1 shows the details on natural gas consumption when exchangers with different effectiveness were used. The analysis was done for colder months (November to March) when space heaters are needed for supplemental heat.

Table J.1 Natural gas consumption (m³/day) in Barn A using heat exchanger with 0.45, 0.60 and 0.70 effectiveness

Month	Heat exchanger with 0.45 effectiveness				Heat exchanger with 0.60 effectiveness				Heat exchanger with 0.70 effectiveness			
	F	N	GF	G	F	N	GF	G	F	N	GF	G
November	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0.51	0	0	0	0	0	0	0	0	0	0
January	0	2.89	0	0	0	0	0	0	0	0	0	0
February	0	2.06	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0

Note: F-farrowing; N-nursery; GF-grow finish; and G-gestation.