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- an examination of heat value

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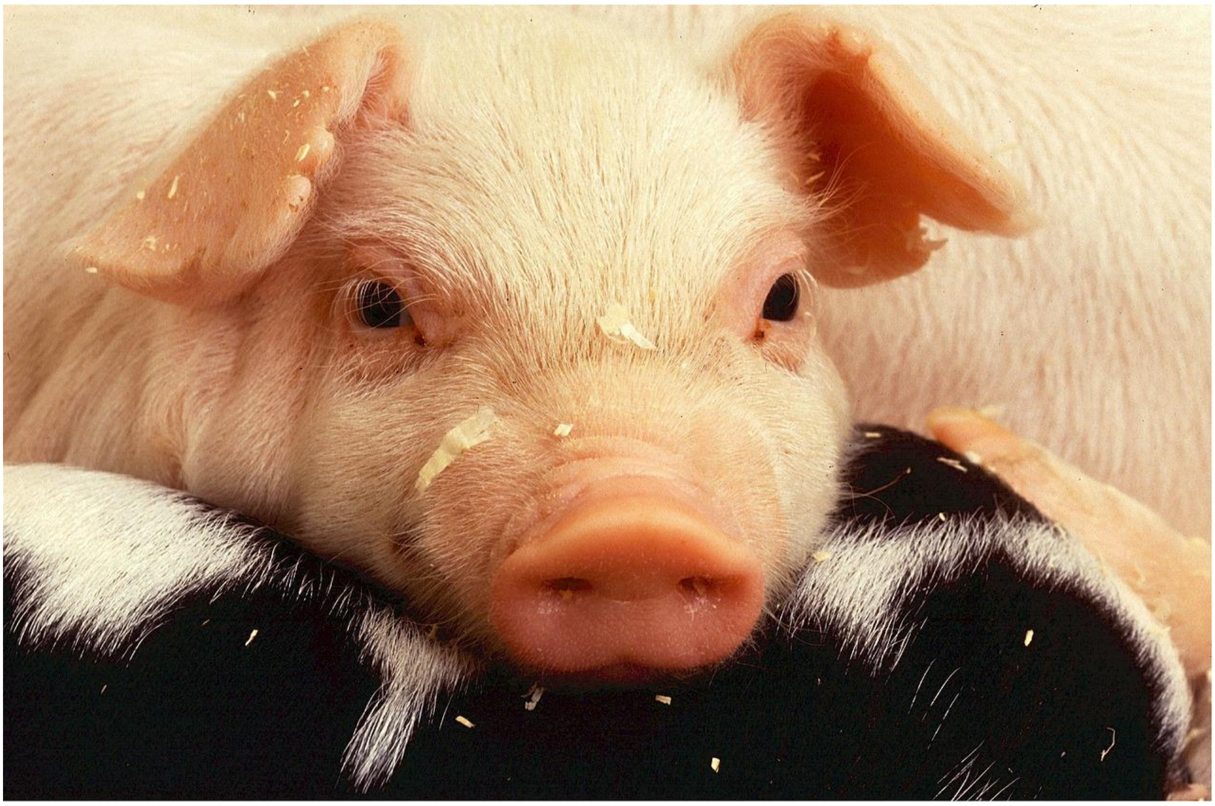

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Sebastian Remvig

Supervisor: Hans Andersson, Swedish University of Agricultural Sciences, Department of Economics

Examiner: Richard Ferguson, Swedish University of Agricultural Sciences, Department of Economics

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Acknowledgements

Dear reader, thank you for finding interest in reading my thesis. If you have experience reading theses you'll probably be a little confused about the layout of this one. This is because I wanted to try out a new format similar to that of a compilation thesis mostly used for doctoral theses. My recommendation is to read in the provided order below but you are free to read any part in the order of your choosing. Thank you to the department of economics staff who encouraged me to try this format and especially to my suprivisor Hans Andersson for the help in making this thesis come to life.

I'd also like to thank the anonymous farmers who contributed with data from their farms. As well as any other person that helped me develop this idea and work.

Abstract/ Summary

Using manure to produce biogas has multiple environmental benefits. However, today Swedish agricultural biogas is generally considered unprofitable meaning it's use is not widespread. This study examines how to properly value heat produced in a combined heat and power unit, an area that has not been studied extensively before. It focuses on how heat can produce synergy effects in pig production by using heat to maintain temperature while increasing ventilation and air quality, a common problem in pig production. A dual case study was preformed where a simulation model described heat use and increased pig performance. Two farms where chosen based on their relative latitude in Sweden to provide maximal temperature differences. Results show that pig performance is improved between 0,82 and 0,95 SEK/kWh used from biogas. This is above the market price of heat and contributed to biogas profitability much more than previous research has suggested. A sensitivity analysis also show that pig performance increase could decrease a ot before heat value is below the break even for biogas profitability. Altering heat use between summer and winter remain a problem in heat utilization from biogas also in this study.

Sammanfattning

Att röta gödsel för att producera biogas har flera miljöfördelar. Trots det är inte teknologin vitt sprid inom svenskt jodbruk, främst på grund av bristande lönsamhet i biogasproduktionen. Denna studie undersöker det verkliga värdet av värme från en kraftvärme generator, ett fält som inte tidigare getts mycket uppmärksamhet av forskningen. Den fokuserar på hur värme kan bidra till synergieffekter i grisproduktion genom att bibehålla temperaturer medan ventilation och luftkvalitet ökas. Bristande luftkvalitet på vintern är ett vanligt problem inom grisproduktion. Två fallstudier genomfördes där en simuleringsmodell beskrev värmeanvändning och förbättrad grisproduktion. Två gårdar valdes utifrån deras geografiska läge för att maximera temperaturskillnader. Resultaten visar att värme som användes för att förbättra grishälsa var värd mellan 0,82 och 0,95 kronor per kilowattimme vilket är högre än marknadsvärdet för värme. För biogasanläggningens lönsamhet betydde detta mycket mer än vad tidigare forskning visat. En känslighetsanalys genomfördes också och visar att grishälsa inte behöver förbättras mycket för att bidra till biogasanläggningars kritiska punkt förlönsamhet. Skillnader i värmeanvändning mellan sommar och vinter är även i den här studien ett problem för biogasanläggningens värmeanvändning.

Abbreviations

ADG: Average daily growth,
CO_{2max}: Restricted concentration of carbon dioxide inside barn,
CO_{2prod}: Carbon dioxide production inside barn,
CO_{2out}: Concentration of carbon dioxide in outside air,
c_p: Specific heat capacity of air,
dT: Difference in temperature between inside and outside,
FE: Feed efficiency,
H_1: Heat use to fulfill scenario 1,
H_2: Heat use to fulfill scenario 2,
H_B: Used heat from biogas
H_{sen}: Sensible heat production,
H_T: Total energy from biogas,
H_{tot}: Total heat production inside barn
H_{trans}: Heat transmission from building,
q_f: Ventilation rate based on moisture balance,
q_k: Ventilation rate based on carbon dioxide balance,
q_v: Ventilation rate based on heat balance,
r: Energy requirement to evaporate water,
t: hours in month,
T_u: Outside temperature,
V_A: cost of cheapest alternative heat source,
V_H: Value of biogas heat,
V_P: Value of improved pig performance,
V_P/H_B: Value of improvement per used kWh.
x: amount of moisture in saturated air,
ρ: density of air, and
φ: Relative humidity in air.

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1 Introduction

According to State public reports (SOU 2007:36) biogas from manure could provide 4-6 TWh/year of energy in Sweden though the production of biogas. This is roughly 1,5 % of the total use of energy in Sweden but more than the entire use in the agricultural sector (Sweden's energy agency, 2017). The potential value of this energy is approximately three billion SEK/year or ca 15 % of current production value in Swedish agriculture (Eurostat, 2017). The environmental benefits of biogas are twofold, it creates renewable energy and prevents greenhouse gas leakage from the manure (Nilsson, 2000). Increased use of biogas from manure could have a positive environmental effect on Swedish agriculture and energy production. However, previous studies in biogas deem the investment into agricultural biogas unprofitable (Edström *et al.*, 2005; Lantz, 2013; Jansson, 2014).

This study examines a clear empirical problem based on the fact that a lack of profitability in biogas production is hindering the development of environmentally sound technology. Economic considerations are necessary in the sustainable development of technology and because of this it is essential that economists conduct research in applied farming. This is the foremost reason for this study into the pig and biogas production system. An investment in agricultural biogas operations is almost always connected to existing livestock operations and form part of a chain in vertical integration (Eliasson *et al.*, 2015). Vertical integration is when the same firm operates in the production of several products where one product is used in the production of the next (Harrigan, 1984). For agricultural biogas vertical integration has always been important with regards to profitability both in terms of procuring substrate to digest but also to use energy on farm. Despite this, the vertical integration framework has not been thoroughly investigated in terms of how the biogas system and operational efficiency is affected. Specifically, this has not been examined with regard to heat.

With regard to heat from biogas it is difficult to assess a definite value on it (Lantz, 2012). In order for businesses to make rational decisions it is vital to be able to prioritize and this is conducted by assessing a monetary value on the resource or product. A problem in vertical integration is that no monetary exchange takes place which means there is no market or pricing mechanism to assert the value. So understanding the value of heat is a theoretical economic question in biogas production. This question needs an answer because the full value of biogas is not understood which might hinder the environmental development of livestock production. To solve the problem without the market as a pricing mechanism the production value of heat can be investigated as an alternative valuation process. The purpose of this study is to evaluate heat from biogas in pig production and to develop an understanding of synergy within the biogas research field. Specifically, the research question is what value heat has in the biogas-pig production system. This is done by conducting a simulation experiment where biogas heat is linked to pig health and production. Through a lens of vertical integration and operational synergy the biogas and pig production system is evaluated. To fully inquire into this aspect it is nececary to examine the system in which this economic problem is situated, in this case the field of livestock production. Parts of this study is therefore conducted outside the tradtional scope of business administration but that is nececary to increase the understanding of the business problem

1. 1 Outline

The study is presented breifly in this summary with extended discussion on methodological, theoretical and analytical perspectives. The main body of research is found in the article manuscript enclosed and in this summary's appendix. The summary starts by describing the theoretical framework and bussines research setting of the study. It contiunes with a methodological presentation and discussion proceeded by descriptions of the simulation model and results of the study. The summary is concluded with the analytical discussion and conclusions as well as a discussion on limitations and contributions of the study.

2 Theory and analytical framework

This study uses an approach based on production and animal welfare economics to explain the concept of operational synergy in an agricultural setting. The concept of synergy has mostly been used in the merger and acquisitions litterature but the concept is applicable in any other investment analysis as well.

2. 1 Production economics

Production economics is a field of study where economic theory is used in the single firm setting and can predict the economic behaviour of firms (Debertin, 2012). It does this by mathematically describing the choices faced by decision makers in the firms and evaluating the optimal action. A popular method in production economics is to create production functions that describe the relationships in production. Debertin (2012, p. 14) define the production function as “the technical relationship that transforms inputs (resources) into outputs (commodities)”. As there was not enough data to simulate the production function in this study a simple quadratic function is used to display the concept used. In this case the production of pigs (P_P) is a function of the use of the resource heat (x).

$$P_p = a + b * x - c * x^2$$

Where *a* is production without using *x*,
b is the positive effect of using *x* and
c is the diminishing returns of using *x*.

From the production function the highest possible production can be calculated, this is where the marginal physical product is zero, at b=2cx (Pindyck & Rubinfeld, 2018). This production serves as a baseline for potential production and biological efficiency at 100 %. However, optimal use for the farmer is dependent on the market prices of products P_P and x. These prices are denoted P_P and P_x. The value of production, U(P), is now a function of x, P_P and P_x rather than just x (Pindyck & Rubinfeld, 2018). It can be described as the following.

$$U(P) = P_p * (a + b * x - c * x^2) - P_x * x$$

Similarly, this equation can give us the most profitable production by calculating the marginal value of product, that is where $P_x=P_P(b-2cx)$. As the price of resourses are genereally larger than zero the efficiency of the production is rarely 100 % of potential biological production.

2. 2 Synergy as a concept

Operational synergy effects arise as an increase in efficiency (Chatterjee, 1986). Efficiency can be described as a percentage of potential production, defined by the production function presented above. The biological efficiency is increased with lowering prices on resources and biogas has an advantage over other heat technologies in this aspect. As biogas produces a fixed amount of heat the marginal price of getting more heat is 0 which means efficiency in pig production can be increased which leads to operational synergies. As heat has decreasing marginal value in the production the extra heat used to increase efficiency presumably have a lower value than market price. Hence market price is not a valid method of evaluating resources used within vertical integration or for evaluating synergy effects.

Even if marginal cost in vertical integration is not 0 there can often be market imperfections that make vertical integration a less costly alternative. Two examples of these market imperfections are that heat generated on the farm cannot be transported without energy losses or that sellers of fuel will charge a transportation fee. Harrigan (1984) states that this type of infrastructure related costs is an important factor in vertical integration. These are also sources of operational synergy but not explicity studied here.

2. 3 Animal welfare economics

Animal welfare economics examines how animal health and economic preformance is related (Lusk & Norwood, 2011). It is a rather new research field and the range of economic approaches are large. A general feature is however that it is used to describe the economic effects of changes in animal welfare which is essentialy how synergy effects aries in the biogas and pig production system. It is known that pneumonia is the disease that affect pig farmers economic returns the most (Straw *et al.*, 1990; Stygar *et al.*, 2016). Pneumonia is linked to lacking air quality, especially in winter when ventilation is reduced to conserve heat (Donham, 1991; Park *et al.*, 2017). Results for other studies show that improvements to air quality benefit the pig's health and its productivity (Choi *et al.*, 2011; Murphy *et al.*, 2012). For a single pig the effect of pneumonia is estimated at 25 % reduced growth and on a herd level improvements to air quality can yield production improvements around 7 % increased growth (Straw *et al.*, 1990; Wathes *et al.*, 2004; Choi *et al.*, 2011).

2. 4 Theoretical synthesis

By evaluating heat dependent on its potential to increase pig production instead of other pricing mechanisms the real value can be examined. Production economics is a good tool for this examination as it can account for interrelations within the farm. The synergy that arises is the result of vertical integration rather than any one production system, meaning they have to be analysed as one unit if any meaningful result is to be achieved. It is therefore nececary to study the causal relationsships between biogas and pig production as presented in Figure 1.

Figure 1. The causal relations leading to synergies between biogas and pig production.

2. 5 Alternative theory

Given the novelty of the approach to evaluate biogas heat with a prespective of resource management and vertical integration I had the freedom to explore different theoretical traditions. For this study the choice fell on production economics as it is a commonly used as an applied theoretical framework to examine economic problems related to farm production and simulation of farm systems. In the study production economics is used to explain how synergy arises in biogas production. Below are some alternative theoretical frameworks that could be used to further develop the field of biogas research.

One alternative theoretical approach is that of institutional economics which discusses how markets, vertical integration and value chains affect the firm. Previous studies strongly indicate that a substantial level of vertical integration is important for biogas profitability (Edström *et al.*, 2008; Jansson, 2014). As an example, electricity produced and used on farm excludes network fees meaning the production cost of electricity can be double that of purchasing but still be profitable because transformation costs are non-existent. As described earlier the restricted marketability of heat from biogas is another problem related to profitability in biogas with which a institutional economics framework would have been valuable.

Another analytical framework that could have been used is the resource based view that offer a perspective on resource use and products. It has been developed to understand the strategic importance of different resources in firms (Greene *et al.*, 1997). Investment in biogas production is certainly a strategic investment and often motivated by resource acquisition (Eliasson *et al.*, 2015). Strategic considerations is a factor that lower investors short term economic expectation on investments (Irani & Love, 2002; Aramyan *et al.*, 2007). Similar to the resource based view is the notion of bricolage presented by Levi-Strauss (1967) together they could have laid the foundation of a qualitative analysis on resource acquisition and management. The theories above were not chosen because a clear quantitative value of heat is needed in the field and that is not the strength of the strategic models presented as alternatives.

3 Method

As previously stated the purpose of this study is to evaluate heat from biogas in the pig production system. Heat has traditionally been part of the biogas analysis and there are concepts of biogas profitability developed but no research on heat synergies exist. This places this study within an intermediate state of research (Edmondson & McManus, 2007). A mixed methods design is appropriate for this type of research as it preserves context but contributes to develop general conclusions. Because of this a deductive case study was performed. This preserves contextual knowledge but with a predefined model to test hypotheses in. To construct this model a litterature review on air quality and pig health was used to provide those parameters to the mathematical model. Further the standards used in Sweden to dimension ventilation in pig barns where used to model ventilation and heat use in the pig production (Swedish Standards Institute, 2014). Data was collected from two case farms and heat use were simulated with the model for those farms. The geographical location was an important reason when choosing the farms and therefore they are called the northern and southern case farms respectivelly. The use of high resolution quantitative material, as the data from the farms, allows for detailed knowledge while also providing general knowledge for wider use.

Case studies are good for complexity and contextual knowledge. This means they are limited in generating context-independent conclussions and results (Bryman & Bell, 2015). As the purpose of this study is to give a general answer to the problem of heat value this might seem to be a methodological inconsistency. However, while case studies are not directly generalizable, the case farms were chosen to maximize differences which increase the generality of the study (Flyvbjerg, 2006). By choosing case farms in the geographical extremes of Sweden the case study becomes a two-tailed case study. The two-tail design of this study means that a range is estabilshed in which all pig production systems should be included and therefore some generality is achieved (Yin, 2009). While this does not generate an average result often sought in quantitative studies it does answer the research question without sacrificing context dependency.

Simulation experiments are “used to mimic a system of interest” (Leemis, 2007, p. 901). The researcher collects appropriate information about the system and develops equations and algorithms to simulate the system. These equations and algorithms are then implemented to analyse the data. This allows the researcher to respond to “what if” questions (Leemis, 2007). In this case the question is; what if heat is used in pig barns to improve pig performance? All models are simplifications of reality and this does mean some information will be lost (Salkind, 2007). Simplifications made in this study are discussed below to allow the reader to evaluate them and some are examples of valuable further research. Another important aspect of simulation is to have exact knowledge on the system-of-analysis. This presents a problem as the pig production litterature does not provide a general consensus on air quality’s effect on pig performance. The lack of exact knowledge meant the use of a production function was not an option for this study. This is a common problem in animal welfare economics (Bennett, 1992).

To examine pig production and air quality a literature review was performed. This literature was largely found in fields outside the scope of this study and after some initial searches a snowball sampling technique from relevant articles was enacted. The critique of snowball sampling is that it increases bias and reduces representativeness (Small, 2009). However, snowball sampling is a good way to analyse the development of a subject area (Allen, 2017). This metohodolgy also allowed for speed which was crucial for the research project. To mitigate both inexperience of the researcher and the critiques of snowball sampling the litterature review was conducted as a critical review. This method impels the researcher to read articles in depth and critically evaluate them (Iyer & Aggleton, 2017). That helps develop understanding on the research field but also to exclude those articles that would not apply in a real-world context (Robson & McCartan, 2016).

3. 1 Validity, reliability and choice of research design

Validity is in many ways the most important quality aspect of research (Bryman & Bell, 2015). It is compartmentalized into four aspects, measurement, internal, ecological and external validity. External and ecological validity concerns the generalisability and applicability respectively (Bryman & Bell, 2015). For this study these issues are closely connected to being able to represent the complexity and contextual aspects of actual farms.

Measurement validity is about whether a measurement is devised to represent the concept under observation (Bryman & Bell, 2015). In this study heat is assumed to be an input in pig production. This is not a direct causal relationship though; heat does not make pigs grow. Instead the use of energy improves air quality (Park *et al.*, 2017), which in turn reduce pneumonia prevalence (Donham, 1991). To achieve measurement validity in this research it is crucial to estimate these causal relationships correctly. To get the causal relationships correct is a matter of internal validity (Bryman & Bell, 2015). When choosing a design for this study high internal validity was prioritized.

Reliability is also an important concern when conducting research (Bryman & Bell, 2015). It can be described as consistency or stability in results. For this study I have used mean and general data when constructing the model which assures the representativeness of the data. However, these means and averages do not present the stability in those data. If we look at Jansson's (2014) study the difference between biogas plants are considerable. For example, the difference in production cost range from 0,3-1,2 SEK/kWh which makes crucial difference in the economic analysis. Therefore, these results will not be stable for the individual case when accounting for context. When doing small sample studies Robson & McCartan (2016) stress the importance of replicability as a reliability aspect. This is something that was focused on when describing details concerning i.e.model construction, simplifications and theoretical assumptions.

The two main aspects when choosing a design for this study was internal validity and representativeness of the conceptual framework. To accommodate that the experimental simulation design was chosen. The experimental design was used because “experiments tend to be very strong in internal validity” (Bryman & Bell, 2015, p. 53). Respectively simulation “is the imitation of the operation of a real-world process or system” (Banks, 2010, p. 21). Together it manages to provide a good methodological fit for the challenges in this study. By choosing simulation, as opposed to a physical experiment, ethical issues that could arise are avoided.

3. 2 Authors influence on result.

This research was conducted from the philosophical viewpoint of pragmatism which does allow the researcher to avoid the traditional dualisms in epistemology and ontology. Instead the researcher is focused on what works and guides action (Robson & McCartan, 2016). Ontologically that means the distinction between objective and subjective is rejected

(Biesenthal, 2014). In this study that has not had a large effect as data has been quantitative and the distinction hasn't made a difference. Instead the ontological assumption is very close to the objectivist paradigm.

In epistemological terms pragmatists regard knowledge by their ability to solve problems (Biesenthal, 2014). Paraphrasing from that can be extracted that knowledge is tool-like. This is important because it allows for incomplete knowledge to be regarded as important research. As long as theory, the tool, is improved a valuable conclussion has been made regardless of the further need for development of the theory. This is one rationale for allowing the simplifications made in this study. Although critics of pragmatism often call it lack of rigour (Biesenthal, 2014). The researcher is aware of the simplifications and the incomplete state of knowledge but that does not decrease the value of the research as the tool is improved. However, future research should try to address these simplifications if the theory, and consequently the tool, is to further improve.

As Cherryholmes (1992) concluded "Pragmatic research is driven by anticipated consequences" (p.14). With this in mind it is prudent to be very careful in the type of assumptions made throughout this study, as anticipation is prone to manifest itself in biases. To mitigate this the assumptions and simplifications are clearly described bellow to allow other researchers to evaluate the eventual shortcomings of this study clearly.

3.3 Ethical considerations

Robson & McCartan (2016) stress that informed consent and anonymity as important ethical considerations in research. As the case study required the farmers to send information on their production consent had to be given beforehand. This was done by telephone were farmers were informed of the study and the wish that they participate was presented. Further information was sent on the study to the participants and a week later they were called again to gain the consent. As participants expressed discomfort in sharing some financial information this was taken out of the study. In general, a lot of data used in this research has been secondary for two reasons. Firstly, to reduce the amount of work necessary for farmers to do and secondly to protect them from any harm that might stem from their data being published. The number of agricultural biogas plants in Sweden is very limited and thus even a small amount of information makes it easy to identify the farmers. The solution was to not use primary data from the farms in some aspects but to use aggregated data from other research then. While a more detailed case might have given even more contextual information of high value this is not the main contribution of the article manuscript and the use of general figures has not decreased the opportunity to examine the problem of heat value.

4 Empirical model

The empirical model used in this study consist of three parts, balance equation model, heat usage model and the pig performance model. The balance equation model was based on those standards already used in the industry to calculate ventilation requirements (Swedish Standards Institute, 2014). From this the minimum ventilation for any given outside temperature can be derived. It consist of three equations that determine balance of a specific parameter, that is where the parameter will not change over time. These parameters are temperature, moisture and carbon dioxide. The actual ventilation is the highest value in either of these three equations. To examine different levels of air quality two different scenarios where defined where balance for carbon dioxide where different. Carbon dioxide is as a proxy for general air quality as research shows the correlaion between the contaminants is high (Donham, 1991; Takai *et al.*, 1998; Peters *et al.*, 2012). For scenario 1 the carbon dioxide level is 3000 ppm which is the legal recuirement in Sweden (SJVFS 2017:25, 171106). For scenario 2 the level is 1500 ppm which has been identified as safe levels for pig health (Donham, 1991). The effects this has on heating in the pig barns can be seen in Figure 2.

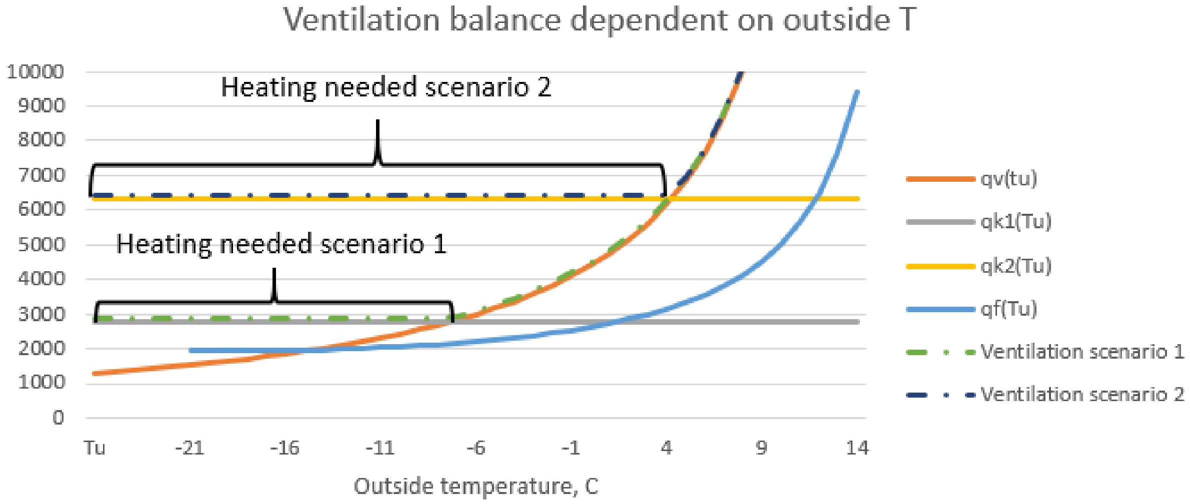

Figure 2. Balance equations for a pig barn at the northern farm.

Heat usage is the next model and build on the fact that pigs perform well within a narrow range of temperature (Choi *et al.*, 2011). Unlike with moisture and carbon dioxide, where maximum levels cannot be exceeded, the temperature must be balanced. When the balance equation for moisture or carbon dioxide is determining ventilation the barn must be heated to preserve temperature. The heat usage model determine the amount of heat used annually. Lastly the pig performance change is estimated with regard to heat from the biogas production. The amount of heat needed to improve air quality is compared to the amount of heat available from biogas and pig performance is improved proportionally. In full the empirical model make the causal case for how air quality can be improved and pig performance enhanced when investing in biogas production.

4. 1 Simplifications and assumptions

To reduce the risk of bias and to increase replicability this chapter presents the assumptions and simplifications made during modelling. It is also important to clearly explain the gaps left by this study to allow further improvement of the theory and methodology in the future.

This study uses balance equations to establish ventilation regimes in pig barns. Usually, these are based on the maximum ventilation requirements to which buildings should be designed. For this study however, the mean weight of pigs during rearing was used. This was an adjustment for the sake of modeling. Because both farms use an all-in-all-out system and the different barns will be at different stages of rearing the assumption is that the collective weight of pigs at any time will be close to the mean weight of pigs during their life. For a barn this was checked to see if heat need progressed linearly or if assuming mean weight wouldn't work. In amounts of heat needed for increased air quality it worked well but it should be pointed out that young pigs need much heat during winter which change scenario 1 requirements. This means that the results of heat needed in scenario 1 is likely underestimated, see Table 1. As this simplification might effect results it is important that future research examines the degree to which this accours.

Table 1. Effects on heat use between different stages of pig growth in southern farm barn.

Weight	30 kg	75 kg	120 kg
Heat need			
Scenario 1	8 408,5 kWh	0 kWh	0 kWh
Scenario 2	133 380,2 kWh	162 327,1 kWh	124 147,8 kWh

Another assumption made in this study was that heating infrastructure was already in place in the stable. This is a simplification that reduce the need to calculate cost of heating infrasturcture. Pig farmers are required by law to be able to heat their barns which is the justification for assuming heating infrastruture is present at every pig barn.

There are evidence that a decrease in pathogens during one production cycle will reduce them in the next as well (Stygar *et al.* 2016). It is hard to estimate how this affect the results of this study. Because of annual variation there will be a natural increase and decrease in air contaminants due to outside temperature and the consequent changes in ventilation. It is possible this fact may change the general balance levels of bacteria in both ways. Pathogens during winter could be generally lower because summer ventilation clears the air. Reversly, the increases in pathogens during winter could persist into the summer. These effects are not included in the study because there is no exact way to measure this within the scope of this study. To account for natural variation in ventilation, the summer months are not counted towards improved pig performance becuase temperature balance increase ventilation naturally.

Because the model is not based on a production function in this study it has not been possible to establish how marginal changes in air quality affect production. Instead two predefined scenarios were used and the production benefits linearly distributed along that improvement. This is counter to the assumption of decreased marginal productivity that is used in micro-economics. However, because ventilation and air quality does not have a linear relationship decreased marginal value of heat stil preserved. It is important that future research is conducted to establish the effect of air quality on pig performance to allow for improved care for pigs.

5 Results

The results of this study show that the value of heat in the pig production is higher than market price for heat, see Table 2. However, the value of energy used was capped at market value as the value of a resource cannot be higher than market value according to accounting principles. Importantly the total heat value is about double that of than 0,04 SEK/kWh which in this study is the break-even point for biogas profitability, which is further developed in the appendix. For the southern case farm there was no heat was used to achive regulation levels in scenario 1 and all heat used is for air quality improvement towards scenario 2. On both farms, heating is used in the period between October and April. Because the outside temperature is higher at the southern case farm the heat available from biogas could improve air quality slitghly more there compared to the northern case farm. This is not reflected in the total heat value as displayed in Table 3 because heat value was capped to the market price. This capping is motivated since it would be unrealistic to value a resource higher than the market price of that resource according to accounting principles. Instead the total heat value presented here better reflects the effects of heat utilization, which is a bit higher on the northern farm. For both case farms heat utilization is over 50 % of available heat but no heat at all is used in the period May-September.

Table 2. Summation of study results.

	Southern case			**Northern case**		
Heat utilization	Used heat as a percentage of biogas energy	Value		Used heat as a percentage of biogas energy	Value	
Scenario 1 heat value	0,0%	0,53	0,000	1,3%	0,53	0,007
Scenario 2 heat value	15,3%	0,53	0,081	14,9%	0,53	0,079
Total heat value, V_H	15,3%		0,081	16,2%		0,086
Pig performance improvement, V_P	344 724			25 385		
V_P per used kWh	1,074			0,92		

6 Discussion

The theoretical assumption is that, with biogas investement, the marginal cost of heat is reduced and accordingly more heat should be used. As a consequence, the marginal value of heat should decrease below market price. The results in this study does not show that, instead the production value of heat is larger than market price for heat. This means that optimal use of heat is larger than biogas heat production and that farmers would have to obtain heat from other sources to act rationally. This is not what is observed empirically (Takai *et al.*, 1998; Peters *et al.*, 2012; Park *et al.*, 2017). The reasons for this difference in observed heat use and rational heat use may be many, as a researcher I started by questioning my method and results. When no apparent misstake was found a sensitivity analysis was conducted to find out how sensetive the results are to changes in pig performance, see Table 3. As biogas profitabilty is maintained despite large changes in pig performance two alternative hypetheses for the suprising results have been formulated.

The first hypothesis is that pig farmers have underestimated the production effects of increased ventilation in pig production and have therefore underutilize heat. What supports this conclusion is that ventilation is normally designed to get rid of excess heat and that could cause farmers to believe that underutilizing heat is not an issue (Park *et al.*, 2017). This would be because farmers have incomplete knowledge of the relation between pig health and air quality and thus act irrational. The cause of this irrational behaviour would then be imperfect information. There could also be a time bias from farmers. Increasing heat has a direct effect resource use and thereby drive cost whereas the pig health benefits manifest themsleves later. A continious research into air quality and pig performance is important because further knowledge could help farmer behave more rationally while simultaneously improving animal welfare.

The second hypothesis of what could have affected the result is seasonal variation. As the model of Stygar *et al.* (2016) show, the bacteria causing disease are transferred between batches. It could be the case that summer ventilation decreases the number of bacteria in the barn which mitigates the lower ventilation and air quality in winter. No study, to my knowledge, has examined the bacterial variation in pig barns due to season but this would be an interesting dynamic issue to examine and would shed some light into how disease loads affect pig production. Seasonal variation is further more a problem in the biogas profitability analysis as heat utilization differs largely due to season. While all heat is utilized in the months November-April there is no use at all in the months May-September on either farm. Increased utilization of heat in summer would improve biogas profitability greatly but is not viable in pig production. Other production that could utilize heat in summer needs to be found and that is an important area of further study.

As stated a sensitivity analysis was preformed to examine how differences in pig performance affected heat value for biogas, see Table 3. The results of the sensitivity analysis reveal that even with low effects to pig performance the total value of heat (V_H) would surpass 0,04 SEK/kWh. This means even if pig performance improvement is overstated in this study it can be so with a substancial margin and still provide biogas profitability. This is important because it shows how large the effect of disease is in livestock farming and that preventive measures have a large effect on farm profitability.

Table 3. Sensitivity analysis to effects on pig performance

IMPACT ON PIG PERFORMANCE	LOW	MEDIUM	HIGH
IMPROVEMENT FEED EFFICIENCY	0 %	2,4 %	6,9 %
IMPROVEMENT ASVERAGE DAILY GROWTH	2 %	7 %	12 %
INCREASED PROFIT PER PIG	20 SEK	82 SEK	153 SEK
V_P/KWH ON SOUTHERN FARM	0,262	1,074	2,004
HEAT VALUE ON SOUTHERN FARM, V_H	0,04	0,16	0,31
V_P/KWH ON NORTHERN FARM	0,224	0,92	1,717
HEAT VALUE ON NORTHERN FARM, V_H	0,04	0,14	0,26

7 Conclusions, contributions and limitations

This study has presented a logical argument for assessing the value of heat from biogas in pig production. A new economic approach to examine heat utilization in the biogas literature has been developed and used. This sheds light on the complexity of biogas production that has previously not been examined by scientists. The study reaches the conclussion that heat value in biogas production is high enough to justify investment since synergy effects develop in the vertically integrated pig production system.

It is good to view the results of this study as preliminary results and to further establish the links between air quality and pig performance. Despite the unestablished state of research of linking air quality and pig production the method of analysis may still serve as a tool for pig farmers and biogas researchers when making further investigations into this subject. It has also established the use of synergies as a concept in the field of biogas literature and shown that its value is higher than previously described in literature. It is also valueable for farmers to know that the return on investment in preventive measures to decrease pneumonia is high. This is mainly due to the fact that both growth and feed efficiency are important factors in pig production profitability.

While this study presents a value on heat from biogas there might be additional economical approaches to utilise heat as a resource in farming. Especially as this study has excluded highly contextualized opportunities but has examined a general solution that would be applicable to every pig farmer. Another example of heat use is green house production of vegetables or flowers. Indeed, this might be done in combination with utilization for barn heat in cold, dark months and green house production in warm, light months when surplus heat is not needed in pig production. This and other possible options to use heat as a resource is interesting but not within the scope of this study. However, they serve as good examples of valuable future research and application of this approach in economic analysis.

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Appendix 1:
Synergy in the pig and biogas production system

1 Introduction

As most areas of human enterprise, livestock production in Sweden faces multiple sustainability challenges. Many farmers are facing low profitability whilst the environmental and social impact of the production is questioned by the public (Dockès & Kling-Eveillard, 2006; Lusk & Norwood, 2011). Especially animal welfare is increasingly included as a social factor in the sustainability analysis (Broom, 2010). Studies show that farmers want to treat animals as best they can but that they are restricted by economic considerations (Dockès & Kling-Eveillard, 2006). Thus, actions for improving the environmental or social performance of the farm is dependent on farm profitability.

Agricultural biogas production from manure provides a way of improving the environmental performance of farms (Nilsson, 2000; Lantz, 2013). However, agricultural biogas is generally not considered profitable under Swedish conditions and is therefore quite uncommon (Jansson, 2014). Part of the problem is that the agricultural biogas production lacks access to markets. When biogas is converted in a combined heat and power unit (CHP) the electricity can be sold to the grid at market value, but heat cannot be transported without large energy losses. This means heat becomes spatially locked on the farm (Edström *et al.*, 2008). While research generally recognizes the importance of utilizing heat to provide profitability it struggles to define the value of heat as it does not operate in a market setting (Lantz, 2012; Jansson, 2014). The focus of this paper is on the use of heat as a resource and as a potential for synergy effects. It does this with a lens of vertical integration and attempts to examine the value of this resource. This poses a new perspective in biogas research when considering heat. This type of reasoning has been used in the biogas literature before but only on the evvaluation of biogas digestate (Blumenstein *et al.*, 2018). Digestate is a biproduct of the biogas production process and face similar problems in terms of marketability.

Heat can be used in a number of ways, often highly contextualised. In order to increase the generalisability of the study, the system-of-analysis is closed and do not require additional buildings or investments apart from the biogas plant, see Figure 1. Specifically, it studies the possibility to create health benefits in pig production by heating pig barns and therefore allowing increased ventilation and air quality. As pig manure is assumed to be the main substrate in biogas production this means the system is closed. In this hypothetical system, farmers can improve sustainablity by simultainiusly improving animal health, environmental and economic preformance. Pig farms are chosen as the system-of-analysis as these animals require heat in winter unlike i.e. ruminants. The aim of this study is to provide a framework for examining synergy effects in verticaly integrated production systems and to evvaluate how synergy contributes to profitability. The aim is achived by simulating heat use for different air quality scenarios and attributing improved pig preformance to biogas heat value. The main research question is to define the value of heat from biogas in pig barns. To answer the main question requires the answers to underlying questions like "when and how does heat use affect air quality?" and "how do pig performance react to changes in air quality?".

The system-of analysis and a visual representation of the research question is presented in Figure 1. Further explainantion of the figure is presented in the empirical model chapter. Basically the system is a representation of monetary flows in a biogas profitability analysis. Without accounting for internal use of heat the profitability of biogas is negative, -0,04 SEK/kWh. Wheather the value of heat is larger than 0,04 SEK/kWh is crucial to justify investment in the biogas venture and to improve farm sustainablity.

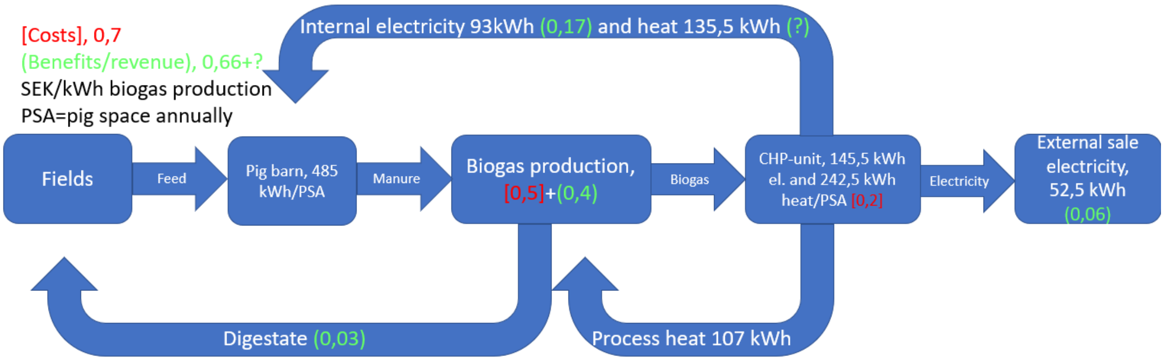

Figure 1. Research system and problem visualisation.

2 Theoretical framework

The purpose of this study is to find out what the value of heat are on the case pig farms. As excess heat is available to the farmer at zero cost increased use of heat is expected according to micro economic theory (Pindyck & Rubinfeld, 2018). Because heat can be seen as a production factor in pig production and the use of this factor increase consequently the pig production will increase, this is called operational synergy effects (Chatterjee, 1986). The effects of operational synergy is the explaination to why two verticaly integrated production systems are more efficient.

Increased heat use compared to heat use under market conditions should according to economic theory be less valuable than heat use up to market optimum, according to the rule of decreasing marginal productivity (Debertin, 2012).Therefore, a study on heat value should distinguish between different heat values. Because heat is always available at market price biogas heat value cannot be higher than that. For increased heat use compared to market conditions the heat value is equal to increased production value in pigs. In theoretical terms solving Equation 1 for V_H is the answer to this study's research question and takes the apporach of system integration.

$$V_H = \frac{H_1}{H_T} * V_A + \frac{V_P}{H_T} \qquad (1)$$

where, V_H is the value of biogas heat;
H_1 is the use of heat under market conditions;
H_T is the production of heat in biogas plant;
V_A is the market value of heat; and,
V_P is the increased value of pig production.

2. 1 Heat use and value

Many studies have already described the profitability of biogas production under different circumstances (Gebrezgabher *et al.*, 2010; Lantz, 2012; Jansson, 2014; Blumenstein *et al.*, 2016; Boldrin *et al.*, 2016; Zema, 2017; Lauer *et al.*, 2018). Some of those, especially under Swedish conditions, discuss the utilization of heat as a key part of the economic performance of the biogas venture (Lantz, 2012; Jansson, 2014). However, none of these studies examine how farms could utilize heat as a resource or in a vertical integration setting. Instead the focus is on defining a market value of the heat produced even if it is used by the farmer. Defining a market value is a difficult task as there are numerous issues to resolve surrounding heat use in agricultural biogas production. Differing heat demand during the year, distance to customer and how much to invest in heat recovery for example (Lantz, 2013). Common ways of dealing with these problems in an economic analysis of biogas are; substitution (Edström *et al.*, 2008; Lauer *et al.*, 2018), statistical assumptions (Lantz, 2012; Blumenstein *et al.*, 2016), perfect markets (Boldrin *et al.*, 2016) or even completely disregarding heat from the economic analysis (Gebrezgabher *et al.*, 2010; Zema, 2017). The approach used in this study, see Equation 1, is most similar to substitution but adds the increased use of heat and subsequent production increases. Another approach to the substition analysis is an ex-post analysis which would factor in increased heat use but fail at accounting for decreased marginal value of heat.

The notion of system integration are not entirely new to the biogas literature as the digestate has similar qualities with respect to its economic value and optimization has been used to evaluate system approaches to biogas production (Blumenstein *et al.*, 2016). It has however been limited to valuation of the biogas digestate when used as a fertilizer. Blumenstein *et al.* (2018) developed an optimization modeling approach to calculate the value possible to attain in German organic farms using a literature review as basis for the model. Similarly, Edström *et al.* (2008) uses a number of experiments as a basis for assumptions on how crop production is changed as a result of biogas digestate utilization. These studies are based on a highly contextualized framework and used to describe complex systems and their interactions concerning biogas digestate. They do not however expand the methodology to include heat use.

So far the assumption has been a deregulated market where productivity is the sole explanitory factor to resource use. This is however not the case as animal welfare regulation also serve a role in explaining heat use in pig production. There are still knowledge gaps in how animal welfare regulation affects economic performance in livestock production (Henningsen *et al.*, 2018). The general assumption is however that economic preformance is reduced as a result of further animal welfare regulation (Harvey *et al.*, 2013). The claim is also rather logical, why would legislation be needed that enforce standards lower than those achieved by the market? Given this it is also approriate to account for heat use levels demanded by legisaltion, in this case (SJVFS 2017:25, 171106) that sets environmental rules for livestock production in Sweden. The amount of heat used to fullfil these regulations will be valued at market value as no farmer has any choice but to abide by the rules, regardless of economic implcations.

2. 2 Air quality and pig health

Possible value attributed to biogas is dependent on affects air quality have on pig production. It has been know for a long time and several studies link lacking air quality to reduced productivity in pig production (Donham, 1991; Pedersen *et al.*, 2000; Murphy *et al.*, 2012). Lacking air quality is related to increased concentration of pollutants in the air such as NH_3, CO_2, endotoxins, pathogens and dust (Peters *et al.*, 2012; Park *et al.*, 2017). However due to the difficulty of analysing and isolating the effects of air quality in general or any particle in particular, the exact effect of the issue is not fully understood (Pedersen *et al.*, 2000; Stärk, 2000; Maes *et al.*, 2018). Numerous studies reveal a difference in air quality between summer and winter, mainly due to decreased ventilation in the winter to conserve heat (Takai *et al.*, 1998; Peters *et al.*, 2012; Park *et al.*, 2017). Studies also reveal that in the winter the concentrations of pollutants increase above the level where swine health deteriorates (Takai *et al.*, 1998; O'Shaughnessy *et al.*, 2009; Park *et al.*, 2017). This suggests that there is a value to use heat, at least in winter, to increase air quality and pig production.

Pneumonia is the leading cause of disease and costs of lacking ventilation (Straw *et al.*, 1990; Stygar *et al.*, 2016). The main contaminants associated with pneumonia are dust, ammonia and bacteria (Donham, 1991). Straw *et al.* (1990) showed that on average a pig with pneumonia have decreased average daily growth (ADG) and lower feed efficiency (FE) with 25 and 20 % respectively. This matches the study by Murphy *et al.* (2012) where pigs were inoculated with bacteria and then exposed to environmental contaminants. The inoculated group that was exposed to bad air quality suffered decreased ADG by 28 % despite not showing clinical symptoms whereas the group exposed only to the bacteria had decreased ADG by 11 %. Another study by Jolie *et al.* (1999) showed that pigs moved from a disease-ridden farm increased ADG by 19,9 % when put in an isolation unit with good ventilation. Murphy *et al.* (2012) and Jolie *et al.*'s (1999) studies did not include FE but Straw *et al.* (1989) used a regression analysis to conclude that FE was reduced by 1,1 times ADG loss minus 5,33.

On a herd level the effects of increased air quality will be lower than the studies cited above as not all pigs are infected. A litterature review was performed to examine the effects on herd level and a visual summary is presented in Figure 2. There are studies that show no correlation between either disease or lacking air quality and ADG or FE (Jansen & Feddes, 1995; Andreasen *et al.*, 2001; Done *et al.*, 2005; von Borell *et al.*, 2007; Michiels *et al.*, 2015). However, Stärk (2000) conclude that many of the studies lack enough complexity to do the matter any justice, this was especially true of experimental studies. Choi *et al.* (2011) studied the effect of temperature and air contaminants on pig performance. Interesting is that the two control groups can be studied where the difference in temperature was not large, but the CO_2 levels were. The decrease in CO_2-levels from 6000 to 2600 ppm resulted in a 7 % increase in ADG on herd level. This corresponds well to a study by Wathes *et al.* (2004) where ADG was reduced by 6,8 % for pigs exposed to high (but not unrealistic) levels of dust and ammonia. Another study showed that pigs exposed to antigens (dust) had produced antibodies which caused the maintenance energy demand to increase and cause a decrease in ADG by between 10 and 15 % Williams *et al.* (1997). As a synthesis from this literature review a 7 % increase in ADG and 2,4 % increase in FE is deemed appropriate. This is applied when improving air quality from regulatory levels (CO_2=3000ppm) to those recommended by Donham (1991) and Fablet *et al.* (2012) which is 1500 ppm.

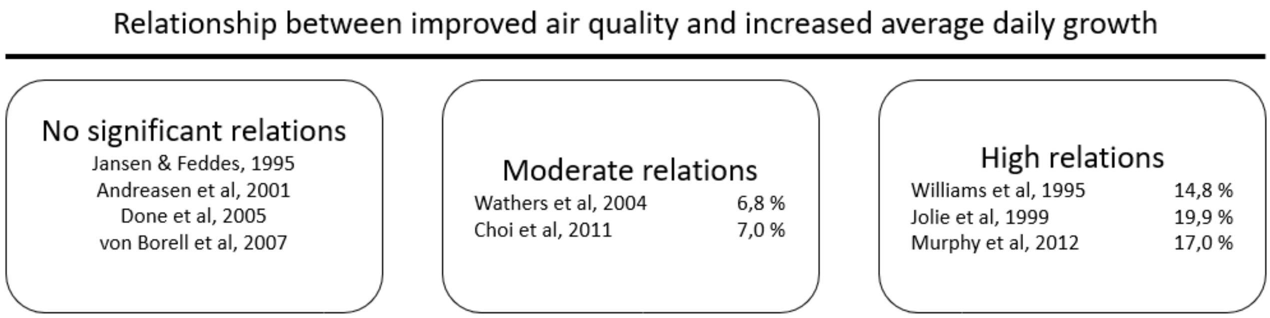

Figure 2. Summary of litterature review

2. 3 Theoretical synthesis

In the sections above the interrelations of biogas and pig production systems have been presented. In short, an investment in biogas with a CHP-unit leads to surplus heat at low cost. This heat can be used to increase ventilation and consequently air quality in pig barns. Increased air quality decrease the prevalence of pneumonia in pigs and decreased pneumonia leads to better growth and feed efficiency in pig production. The integrated analysis will use as much heat as possible to increase air quality and maximize the effects to pig preformance. In contrast the non-integrated analysis will assume heat use to fulfill regulatory demand and the production results will be average for the Swedish context. This short summary could be concieved as the qualitative explanation to the research problem. The aim of the study is to quantify this explaination and provide meaning with regards to the investment decision facing pig farmers.

3 Method

To answer the research question the interrelations presented in the theoretical synthesis must be quantified. Thus, several underlying questions must be answered to establish the relationships and quantify values within the vertically integrated system. Three underlying questions were formulated and two strategies for obtaining answers produced. These questions were as follows:

1. What is the benefit to pig performance from improved air quality?
2. When in the yearly cycle is heat used and how?
3. What is the relationship between heat use and improved air quality?

To answer the questions research were divided between desk research and empirical research. The two latter questions were chosen to be empirically studied and two case farms were chosen to provide the empirical data nececary for simulation modeling. As the first question is in itself a worthy subject for study a review of existing litterature was preformed. In full the present study has been performed with a deductive approach were the empirical data is put into an already developed quantitative model to produce a result. The results are then compared to the underlying assumptions and theory in order to find where further theory needs to be developed to understand the issue.

As already described, there is no consensus as to the relationship between pig performance and air quality. Because there is a lack of previous research and empirical data no production function could be estimated. A production function would be the preferred methodology in this kind of production economic setting (McInerney *et al.*, 1992). It is common for studies in animal welfare to lack this kind of information (Bennett, 1992). The lack of consensus in the field warranted a critical literature review to assert what might be reasonable to assume in practical research and for practitioners. Literature was chosen with a snowball methodology in order to follow the development of the subject matter through time and to give a fast introduction to the subject (Allen, 2017). The aim of the review has been to provide a probable effect of air quality on pig production profitability. To reach such a meta-synthesis some research has to be rejected as practically unfeasible and this goes beyond the traditional literature review (Robson & McCartan, 2016).

To increase practical value and generalisability the two empirical questions will be answered by a dual case study. The cases have been chosen to give the bipolar extremes in terms of energy use which makes general conclusions more plausible (Flyvbjerg, 2006; Yin, 2009). Because case studies allow the researcher to be particular with respect to context it has value in describing the problem clearly (Robson & McCartan, 2016). Also economic figures for biogas production are general for this matter. The simulation models are based on the current standard for ventilation dimensioning which increase the validity and practical nature of the study. These standards are based on balance equation which provide the status quo scenario which means input data can be quite sparse. The models are based on means during the year and pig production for simplification. Models are simplifications of reality meaning general assumptions take some president over contextualized knowledge (Salkind, 2007; Debertin, 2012). These simplicifactions are designed not to interfere with the average or with the result of the study but does so at the expense of the specific.

3 . 1 Case descriptions

Two pig farms with biogas production was chosen for their relative position in Sweden, one in the most southern and the other in the most northern part. Both farms provided building data on barn dimensions, building insolation and inside temperature for each barn. They also contributed with data on pig weight at start and finish and number of pigs in every barn. The farmers on both farms have provided a detailed description of their finishing pig barns and from that the heat, carbon dioxide and moisture balances in the barn can be derived. Whilst both farms have farrow-to-finish production only the finishing operation will be analysed because a full description of their operation would be too cumbersome for the farmers with respect to time. The literature does suggest that pneumonia in piglets is just as important as for pigs if not more so (Morris *et al.*, 1995; Williams *et al.*, 1997).

Ventilation is usually designed to get rid of excess heat from the pig barn during summer (Takai *et al.*, 1998; Park *et al.*, 2017). This means that need for heat varies over the year and is negative during some months of the year. This is because the respiration of pigs yields the production of heat inside the barn. Therefore, an analysis of the difference between the north and south of Sweden is interesting as the temperature differences are maximized that way. Heat balance in the barn are of course also subject to change depending on building parameters such as size, insulation and production system.

The northern farm has two finishing barns that are a mirror pair and for the sake of ventilation in them identical. They have 190 pig spaces each and relatively good insulation. Based on weather data from close by Sundsvall airport the average monthly temperature (Tu) and relative humidity (φuv) has been extracted, see Table 1. The temperature inside the barns are set to 17 °C by the farmer. The mean weight of pigs during their time in the barn is 79 kg.

Table 1. Environmental monthly facotrs for the northern farm.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Tu, °C	-7,47	-6,93	-2,35	2,45	8,11	13,21	15,75	14,38	9,85	4,32	-1,20	-5,44	3,80
φuv, %	89,14	87,33	77,51	71,90	69,81	68,84	72,46	78,32	84,32	85,09	90,84	90,78	80,17

The southern farm has ten finishing barns with four mirror pairs and two independent barns. As with the northern farm weather data was gathered at a nearby weather station in Hörby, shown in Table 2. Together the ten barns contain 4314 pig spaces and inside temperature gradually decrease over the course of finishing with 22 °C at start and 17 °C before slaughter. The mean weight of the live pigs in the barn is 75 kg. Descriptions of the barns on the both farms are provided after the references.

Table 2 Environmental monthly factors for the southern farm.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Tu, °C	-0,33	-0,14	2,09	7,04	11,61	14,75	17,15	16,79	13,13	8,53	4,27	1,02	7,99
φuv, %	90,80	88,56	81,69	73,18	72,25	75,05	77,33	79,62	83,36	87,69	91,03	92,17	82,73

3. 2 Scenario descriptions

Two scenarios will be modeled for the two case farms regarding the air quality in the pig barns. Gases usually used for this assessment are either ammonia or carbon dioxide. This is appropriate as the correlation between different air contaminants is high (Donham, 1991; Cargill *et al.*, 2002; Fablet *et al.*, 2012). In this study the concentrations of carbon dioxide will be analysed as it is used to make balance equations with respect to ventilation (Swedish Standards Institute, 2014). As described in the theroy chapter the two levels of carbon dioxide are set according to regulatory demands (3000 ppm CO_2) called scenario 1 and healthy levels accoring to research (1500 ppm CO_2) called scenario 2.

4 Empirical model - heat use

When dimensioning ventilation in pig barns three environmental factors are accounted for temperature, moisture and carbon dioxide (Swedish Standards Institute, 2014). This is done by using balance equations. These equations produce the value for ventialtion levels that keeps the factors balanced and the highest will determine ventilation volumes, see Figure 3. For moisture and carbon dioxide increasing ventialtion compared to the balance is not a problem as these are minimum requirements. Temperature however needs to be maintained within a spectrum to keep pigs comfortable and needs to be balanced (Choi *et al.*, 2011). This means if ventilation is higher than balance for temperature the extra air needs to be heated or temperature drops. Increasing ventilation requirements for carbon dioxide will therefore increase the amount of heat needed. Figure 3 shows that between the two scenarios there are differences in terms of when heat (qv) becomes the determening balance and air no longer need to be heated. By calculating the balance equations for each barn under the temperature conditions for each month the annual heating in the two scenarios are recived.

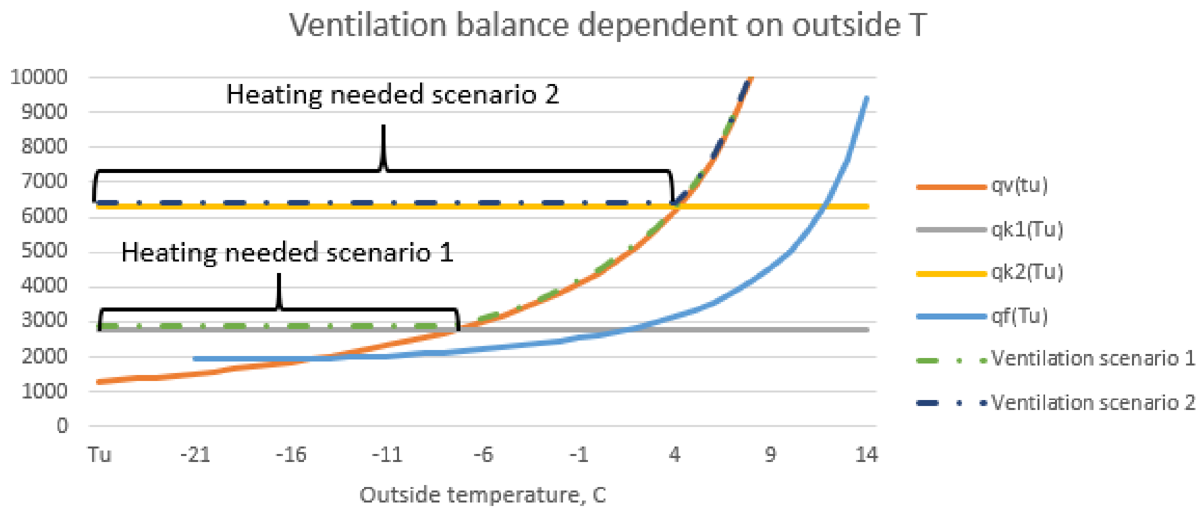

Figure 3. Balance equations for a barn on the northern farm.

4. 1 Balance equations for ventilation dimensioning

Each balance equation is dependent on different factors which means they are differently affected by outside temperatures. For carbon dioxide the balance equation is not dependent at all on the outside temperature, but on the total respiration from the animals and manure in the barn. That means the generation of carbon dioxide is constant given the same number of pigs and manure in the barn, see Equation 2. The temperature balance on the other hand is dependent on outside temperature as the difference between inside and outside air temperature determines how much air must be replaced, see Euqation 3. Moisture in the barn is dependent on the moisture production (sweat) and the difference of absolute moisture in inside and outside air. This is to some extent dependent on temperatures, see Equation 4.

$$qk = \frac{CO_{2prod}}{CO_{2S} - CO_{2out}} \qquad (2)$$

Where, qk (m^3/h) is the carbon dioxide balance ventialtion;
CO_{2prod} (m^3/h) is carbon dioxide production equal to total heat production (H_{tot}) times 0,185 (Pedersen *et al.*, 2002);
CO_{2S} (ppm) is the concentration of carbon dioxide in the barn set for each scenario; and

CO_{2out} (ppm) is outside concentration of carbon dioxide, set to 330 (Swedish Standards Institute, 2014).

$$qv = \frac{Hsen - Htrans}{c_p * dT} \qquad (3)$$

Where, qv (m^3/h) is the temperature balance ventilation;
H_{sen} (W) is sensible heat, equals $H_{tot}*(0,62-1,15*10^{-7}*T_{in}^6)$ (Pedersen *et al.*, 2002);
H_{trans} (W) is the transmission heat dependent on dT and the insolation capacity of the specific barn (Swedish Standards Institute, 2014);
c_p is the specific heat capacity of air, set to 0,33; and
dT is the difference in outside and inside temperature in °C.

$$qf = \frac{(H_{tot} - H_{sen})/r}{\rho * (\varphi_{in} * x_{in} - \varphi_{out} * x_{out})} \qquad (4)$$

Where, qf (m^3/h) is the moisture balance ventilation;
H_{tot} (W) is the total heat production (Pedersen *et al.* 2002);
H_{sen} is the sensible heat (Pedersen *et al.*, 2002);
r (Wh/g) is the heat required to evaporate water (Pedersen *et al.*, 2002);
ρ (kg/m^3) is the density of air, set to 1,25;
φ (%) is the relative moisture in the air; and
x (g/m^3) is the moisture in saturated air as a function of temperature T (°C) where $x = 0,0107T^2 + 0,3863T + 4,7344$ (*Maximum Moisture Capacity of Air*, 2008).

4. 2 Additional heat

When balance equations are calculated for every barn and every month of the year the total heat is calculated, see Equation 5. This is conducted by taking the highest balance equation value and substracting the heat balance to recive the amount of air needed to heat and multipling in how much energy will be needed to heat that air. This equation is used for H_1 in Equation 1 and for H_2 in Equation 6.

$$\mathrm{H} = \sum_{i=1}^{12}((\mathrm{Max}(qk, \mathrm{qv}, \mathrm{qf}) - \mathrm{qv}) * \mathrm{dT} * c_p * \mathrm{t}) \qquad (5)$$

Where, H (kWh) is the heat needed, denoted as 1 or 2 depending on scenario;
qk, qf and qv are taken from (2), (4) and (3) respectively; and
t is the number of hours in the month.

5 Empirical model – economic impacts

There are three prime economic impacts the model has to account for. These are the cost of biogas production, economic value of increased pig production and market cost of heat. Each is quantified and the role is expalined for the model.

5. 1 Cost of biogas production

According to Jansson (2014) the average production cost in Swedish biogas production has been accounted to 0,7 SEK/kWh after investment support from the Swedish government. The income from biogas production with a CHP-unit includes methane reduction support, electricity sales, increased value of digestate as fertilizer and the value of internal use of energy, see Table 3 For every pig space the annual manure production is 3,1 tonnes and the energy in every tonne is 156,6 kWh meaning every pig space provides 485 kWh/year denoted as H_T (Edström *et al.*, 2008; Swedish Bord of Agriculture, 2017).

Use of electricity internally at the farm has higher value as the farmer does not have to pay a network fee. On average a Swedish pig barn uses 93 kWh electricity per pig space annually (Neuman, 2009). The biogas production process requires heat to operate and 22 % of produced energy will be reused as process heat. The rest of heat energy is available for use in the pig barns, the value of which is the research question of this study and therefore not evaluated. The profitability breakdown of biogas production is presented in Table 3.

Table 3. Break down of biogas profitability without valuing heat.

Activity	Reference	Revenue, SEK/kWh	Amount/PSA, kWh (%)	Value for production, SEK/kWh
Biogas production	(Jansson, 2014)	-0,5	485 (100)	-0,5
Biogas combustion	(Jansson, 2014)	-0,2	485 (100)	-0,2
Internal electricity	(Lantz, 2012) + updated statistics	0,38+0,12+0,37 =0,87	93 (19,2)	0,17
Electricity sales	(Lantz, 2012) + updated statistics	0,38+0,12+0,05 =0,55	52,5 (10,8)	0,06
Digestate	(Edström *et al.*, 2008)	0,03	485 (100)	0,03
Methane reduction support	(SFS 2014:1528)	0,4	485 (100)	0,4
			Sum	**-0,04**

5. 2 Increased pig production

The benefits to pig health when carbon dioxide is reduced from 3000 to 1500 ppm are increased average daily growth (ADG) and feed efficiency (FE). Using modern Swedish data from *Agriwise* (2017) the improved pig performance can be quantified and expressed in monetary value. Increasing ADG by 7 % and FE by 2,4 %, as concluded in the theory chapter, leads to a 82 SEK/pig increase in profitability. Based on 3,2 pigs/pig space annualy (PSA) the total value is 262,4 SEK/PSA.

The effects to increased profits should however be corrected for the portion of the year that these benefits manifest themselves. During some months the heat balance equation will force ventilation in scenario 1 to be higher than minimum CO_2 rates but not as high as minimum

CO_2 rate in scenario 2. This is handled by assuming that benefits are linearly divided throughout the use of heat. This maintains the theoretical assumption of decreased marginal value of heat as the marginal effect of ventilation of air quality is decreasing. During months when heat balance increase ventialtion rates the benefits will be counted as the portion of air improvement still needed to reduce carbon dioxide to 1500 ppm. The full value of a month is therefore 262,4/12= 21,87 SEK/month. 21,87 is then multiplied with the percentage of air improvement related to heat from biogas. Meaning that in total V_P from Equation (1) is defined as follows:

$$V_p = PS * \sum_{i=1}^{12} 21{,}87 * \frac{H_B}{(qk_2 - qk_1) * dT * c_o * t} \quad (6)$$

Where, V_P (SEK) is improved pig performance;
PS is pig spaces; and
H_B is available heat from biogas, restricted by ($H_B \leq H_2$).

5. 3 Market cost for alternative heat sources

If biogas was not available the farmers would need heat from another source. (Edström *et al.*, 2008) finds that wooden pellets is the cheapest alternative at 0,41 SEK/kWh. Adjusting for inflation the current price of wooden pellets is 0,53 SEK/kWh (*Pelletsforbundet.se, 2018*). In the analysis the energy needed in scenario 1 is valued at 0,53 SEK/kWh (V_A) as this heat use is demanded by regulation. The remaining energy used will be valued based on the production benefits it provides to the pig performance (V_P) as described below. However, 0,53 SEK/kWh is set as a ceiling value as heat can be procured to that cost no matter the production value and therefore cannot be worth more either.

6 Results

Table 4. Balance equations and heat use on the southern farm.

	Southern farm	Scenario 1	Scenario 2
		CO_2 balance (eq. 2) 61 245 m³/h	*CO_2 balance (eq. 2)* 139 765 m³/h
	Heat balance (eq. 3, m³/h)	Heat use (eq. 5, kWh)	Heat use (eq. 5, kWh)
Jan	64 814	0	364 954
Feb	65 582	0	323 144
Mar	75 888	0	273 036
Apr	111 944	0	82 331
Maj	185 275	0	0
Jun	317 516	0	0
Jul	657 089	0	0
Aug	566 566	0	0
Sep	233 021	0	0
Oct	129 100	0	28 724
Nov	88 830	0	184 369
Dec	70 617	0	313 816
		0	**1 570 374**

Table 5. Balance equations and heat use on the northern farm.

	Northern farm	Scenario 1	Scenario 2
		CO_2 balance (eq. 2) 5 528 m³/h	*CO_2 balance (eq. 2)* 12 616 m³/h
	Heat balance (eq. 3, m³/h)	Heat use (eq. 5, kWh)	Heat use (eq. 5, kWh)
Jan	5 245	1 733	42 476
Feb	5 394	726	36 722
Mar	7 001	0	25 294
Apr	9 853	0	8 893
Maj	17 668	0	0
Jun	51 966	0	0
Jul	578 507	0	0
Aug	89 870	0	0
Sep	22 982	0	0
Oct	11 595	0	2 928
Nov	7 537	0	20 759
Dec	5 839	0	35 680
		2 459	**172 753**

The results for the model show that for every month on these two farms either temperature balance (3) or CO_2 balance (5) are the deciding equations for ventilation rate in pig barns. This means that moisture balance (4) was not necessary and are not present in the tables below. Because the value of the heat used is larger than market value the heat value (V_H) and the production value (V_P) does not correspond to each other. To illustrate the production value of heat the term V_P/H_B is introduced. Both farms V_P/H_B are higher than the market cost of heat which means heat value is based on market value of heat (V_A).

6. 1 Heat use

Results from the southern case farm are presented in Table 4. With regard to carbon dioxide the ventilation rate needed is 61 245 and 139 765 m³/h for the 10 barns in scenario 1 and 2 respectively. The heat balance varied between 64 814 and 657 089 m³/h over the course of the year. In scenario 1 there is no extra heating needed at all. In scenario 2 the months October-April require extra heating. January is the month with the highest heat demand at 364 954 kWh and demand decreases with increasing outside temperatures. Total heat use is 1 570 374 kWh in scenario 2 which is equal to 364 kWh/pig space.

The results from the northern case farm are presented in Table 5. The ventilation rates needed in the two barns are 5 528 and 12 616 m³/h respectively in scenario 1 and 2 to satisfy carbon dioxide balance equations. The heat balance varies over the year according to outside temperatures from 5 245 to 578 507 m³/h. January and Febuary both require heating in scenario 1 wheras for scenario 2 the same months as on the southern farm require extra heating. Total heat useage in scenario 1 is 2 456 kWh and for scenario 2 it is 172 153 kWh. Per pig space the usage is 6,5 and 453 kWh for scenario 1 and 2 respectively.

6. 2 Air quality improvement and economic impact

For those months where air quality improvement is possible the amount of biogas heat available is not enough to increase air quality from 3 000 to 1 500 ppm. Instead the improvement is between 6 % and 21 % value of this increase in air quality, see Tables 6 and 8. That means the economic impact is considerably less than the potential 262,4 SEK/PS between 20,88 and 23,36 SEK/PS. Despite this the economic value of heat used is higher than the market value of heat, see Table 7. This simulation estimates the value of heat from biogas to the pig production system to be 0,081-0,086 SEK/kWh which is substantially higher than the 0,04 SEK/kWh nececary to deem the biogas venture profitable. At the southern farm 320 997 kWh of biogas heat is used out of 584 547 kWh available due to no useduring summer months, this puts heat utilization at 54,9 % from the biogas production. At the northern farm 29 921 kWh are utilized of the total 51 300 putting the heat utilization rate at 58,3 %. For the two biogas cases utilized heat is 15,3-16,2 % of total energy produced.

Table 6. Air quality improvement and economic impact on sourthern farm.

Southern farm

	Unused biogas heat to scenario 2 (kWh)	**Improvement potential (H_2-H_1, kWh)**	**Percentage improvement**	**Value improvement (SEK/PS)**
Jan	48 712	364 954	13%	2,79
Feb	48 712	323 144	14%	3,11
Mar	48 712	273 036	15%	3,17
Apr	48 712	82 331	21%	4,58
Maj	48 712	0	0%	0
Jun	48 712	0	0%	0
Jul	48 712	0	0%	0
Aug	48 712	0	0%	0
Sep	48 712	0	0%	0
Oct	48 712	28 724	14%	2,97
Nov	48 712	184 369	17%	3,75
Dec	48 712	313 816	14%	2,99
Sum	**584 547**	**1 570 374**	**Value PSA**	23,36 SEK
			Total farm value	344 724 SEK

Table 7. Economic results of the simulation.

	Southern farm			**Northern farm**		
Heat value	H/H_T	V_A, V_P	SEK/H_T	H/H_T	V_A, V_P	SEK/H_T
Scenario 1	0,0%	0,53	0,000	1,3%	0,53	0,007
Scenario 2	15,3%	0,53	0,081	14,9%	0,53	0,079
Total heat value, V_H	15,3%		0,081	16,2%		0,086
Total, V_P, (SEK)	344 724			25 385		
V_P/H_B, (SEK)	1,074			0,92		

Table 8. Air quality improvement and economic impact on northern farm.

Northern farm	Unused biogas heat to scenario 2 (kWh)	Improvement potential (H_2-H_1, kWh)	Percentage improvement	Value improvement (SEK/PS)
Jan	2 542	40 743	6%	1,36
Feb	3 549	35 996	10%	2,16
Mar	4 275	25 294	13%	2,93
Apr	4 275	8 893	19%	4,10
Maj	4 275	0	0%	0
Jun	4 275	0	0%	0
Jul	4 275	0	0%	0
Aug	4 275	0	0%	0
Sep	4 275	0	0%	0
Oct	4 275	2 928	21%	4,60
Nov	4 275	20 759	15%	3,23
Dec	4 275	35 680	11%	2,51
Sum	**48 841**	**170 293**	**Value PSA**	20,88 SEK
			Total farm value	25 385 SEK

7 Discussion

The value of heat energy in pig barns has been investigated. For the two farms the value per kWh used for improvement are surprisingly similar at ca 0,08 SEK/kWh despite their difference in geographical location. This is a result of the fact that seasonal changes are quite similar and therefore heat is applied during the same months. On both farms there is not enoguh heat to reach scenario 2 levels of air quality. This is one reason for why the value of heat is similar on both cases. The northern farm would use 91 kWh more per pig space and year if that heat was available. While heat is only needed at the northern farm in scenario 1 the large increase in heating need in scenario 2 means that heat can be used in pig barns throughout Sweden. This might be counterintuitive to farmers as ventilation systems are normally used to get rid of excess heat rather than decrease air pollutants (Takai *et al.*, 1998; Park *et al.*, 2017).

The economic improvement of pig production is above the threshold of 0,04 SEK/kWh needed to make the average biogas plant in Sweden profitable. Both farms manage to utilize more than 50 % of heat energy which is one key component according to Edström *et al.* (2008). In both farms heat use with biogas shows full utilization in the period November-April which is also quite interesting, perhaps this would have changed if the southern farm had used the same inside temperature as the northern farm. Similarly, in October there are some leftover heat after improvement of air quality while the period May-September need no additional heating supplement. That does explain the similarities in heat utilization percentages on the two farms. However, it poses a problem for farmers as summers are the time of year where increases in heat utilization is hard to achieve and the results of this study do not address that problem. Edström *et al.* (2008) as well as many other scholars use heating of housing as the main utilization of heat as a product and find problems using heat in summer. Increasing heat utilization in summer would be the area where the most benefits to profitability could be found. Another path to increased heat utilization would be to increase biogas production in winter and decrease it in summer though demand driven production. This does demand higher investment cost than a traditional biogas plant as well as more managerial work (Ertem & Acheampong, 2018). This has usually been regarded as uninteresting as heat can be procured cheaply (Lantz, 2012). However, the high value of heat energy presented above make the study of this phenomena interesting.

The effect of increased air quality on pig performance is estimation and requires further study in the future. The effect on FE and ADG have large economic consequences and is highly contextual which means individual differences between pig farms are likely if studied empirically. A caution should be raised as the value of heat in this study is larger than market price for heat which means it would be possible for all farmers to use heat to increase production results. This is not what was expected based on the theoretical approach and further study should be conducted to further examine the value of heat in pig production. Perferably with data good enoguh to preform a regression analysis with good reliability. Based on the literature reviewed in this study a sensitivity analysis was preformed to examine the range of effect on the farms economic performance. A 5 % change in ADG and FE was introduced to find out how large the economic impact would be, see Table 9. As the economic value of increased growth and feed efficiency is quite high the break even point for biogas heat is about 75 % lower than what is assumed in this study and thus even a 2 % increase in ADG without an increase in FE would result in profitable biogas heat utilization.

Table 9. Sensitivity analysis to effects on pig performance

IMPACT ON PERFORMANCE	LOW	MEDIUM	HIGH
IMPROVEMENT FE	0 %	2,4 %	6,9 %
IMPROVEMENT ADG	2 %	7 %	12 %
INCREASED PROFIT PER PIG	20 SEK	82 SEK	153 SEK
V_P/KWH ON SOUTHERN FARM	0,262	1,074	2,004
HEAT VALUE ON SOUTHERN FARM V_H	0,04	0,16	0,31
V_P/KWH ON NORTHERN FARM	0,224	0,92	1,717
HEAT VALUE ON NORTHERN FARM	0,04	0,14	0,26

The cost of increasing ventilation rates has not previously been raised in this study but is of little consequence. As ventilation capacity to achieve scenario 2 ventilation rates is already required during summers no extra investment is needed. The variable cost is also low, 1 kWh of energy replace 4 280 m^3 at a cost of 0,8 SEK (Park *et al.*, 2017). Hence, the 370 000 m^3 of air needed to gain scenario 2 in the southern farm would cost less than 70 SEK to ventilate which is negligible.

8 Conclusions

Using surplus heat from biogas production to improve air quality in finishing operations for pigs increases pig performance and enhances profitability for farms. The effect is large enough to validate investment in biogas production on pig farms in Sweden because of the substansial synergy effects. The problem of underutilized heat in summer remains an issue. Heat utilization was improved to above 50 % on both case farms but no heat was needed in the months May to September so finding ways to increase heat use in those months would be economically optimal. However, when using heat to increase air quality all used heat can be evaluated at market price which is higher than what was expected.

This new approach on heat utilization in agricultural biogas production may be used to provide a more complex and realistic value of heat in biogas production. This study has shown the risk of faulty conclusions that are obtained if these complex interrelations and synergy effects are not considered. This study provides the necessary theoretical framework for further research and analysis of biogas profitability.

8. 1 Future research

More research is needed in the pig production literature on the effects of air quality on pig performance. Examination of seasonal changes in bacterial counts, prevalence of pneumonia and pig growth are good examples of possible research that could provide this type of analysis higher validity. Cross sectional studies of many pig barns and the air quality’s relation to prevanalce of diseace could unlock the possibility of estimating production functions. Also the investigation of these aspects in an empirical setting would provide much needed contextual understanding of the interrelations between biogas and pig production.

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Appendix 1.1: Pig barn dimensions

Northern farm

Barn 1 and 2:	Number of pig per barn – 190		Inside temperature – 16 °C
	Start weight – 28 kg		Finished weight – 130 kg
	Width – 6 m	Hight – 3 m	Length – 38 m
	Isolation capacity – 172,8		

Southern farm

Barn 1 and 2:	Number of pig per barn – 540		Inside temperature – 22-17 °C
	Start weight – 30 kg		Finished weight – 120 kg
	Width – 14 m	Hight – 3 m	Length – 52 m
	Isolation capacity – 709,9		
Barn 3 and 4:	Number of pig per barn – 400		Inside temperature – 22-17 °C
	Start weight – 30 kg		Finished weight – 120 kg
	Width – 8 m	Hight – 3 m	Length – 72 m
	Isolation capacity – 532,8		
Barn 5:	Number of pig per barn – 234		Inside temperature – 22-17 °C
	Start weight – 30 kg		Finished weight – 120 kg
	Width – 10 m	Hight – 2,6 m	Length – 30 m
	Isolation capacity – 303,6		
Barn 6:	Number of pig per barn – 440		Inside temperature – 22-17 °C
	Start weight – 30 kg		Finished weight – 120 kg
	Width – 18 m	Hight – 3 m	Length – 40 m
	Isolation capacity – 610,2		
Barn 7 and 8:	Number of pig per barn – 400		Inside temperature – 22-17 °C
	Start weight – 30 kg		Finished weight – 120 kg
	Width – 16 m	Hight – 3,2 m	Length – 40 m
	Isolation capacity – 343		
Barn 9 and 10:	Number of pig per barn – 480		Inside temperature – 22-17 °C
	Start weight – 30 kg		Finished weight – 120 kg
	Width – 16 m	Hight – 3,2 m	Length – 46 m
	Isolation capacity – 391,9		