Optimal Use of the Generated Biogas from Manure

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Abstract

This paper presents the results of an optimisation algorithm for biogas use. There is considered the case of the big farms. Generated biogas from manure is an important energy resource. The goal of the research is to estimate how biogas can cover the energy demand of the farms. Special software has been developed for managing the energy, environmental and economy balances. The best approach is to use biogas for producing heat and power. One can assume different heating schedules and electricity needs. Energy consumption for hog, poultry, beef and dairy farms can be simulated. The potential of the generated biogas is estimated using specific indicators. The software is able to find the optimal size of the biogas engine and boiler for different cases. The energy production is compared with the needs of the farm. As a result, there are presented financial analysis of valorisation projects for different types of animal farm.

Keywords: Biogas, Manure, Optimisation, Pollution reduction, Energy demand, Financial efficiency

Introduction

In today's energy conscious world, alternative forms of energy become more and more important for deciding the future of the world's energy needs. In addition to pollution, depletion is another problem that concerns fossil fuels. The idea of generating methane gas from manure has considerable merit because it appears to offer at least a partial solution for the presented problems. Livestock manure contains a portion of volatile (organic) solids (VS) that are fats, carbohydrates, proteins and other nutrients that are available as food and energy for the growth and reproduction of anaerobic bacteria.

The process where the organic content of the manure is transformed in biogas is named anaerobic digestion (AD). The AD is a biological process, where synergistic action between bacteria is occurring at four different levels. First, hydrolysis converts a wide range of solid organic materials into sugars and amino acids. Fermenting these materials produces volatile fatty acids (VFAs). Acidogenesis forms hydrogen, carbon dioxide (CO_2), and acetate from VFAs. Finally, methanogenesis produces biogas, a mixture of methane, CO_2 and numerous traces of other elements [US DOE.1996].

In order to develop these reactions, is needed a constant temperature. Heat demand is added to the energy consumption of the farms. Having the fuel source and the energy

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demand, at the same place and at the same time, represents an important opportunity. An engine can burn the biogas, for electricity production. The recovered heat from exhausted gases is used for maintaining the AD process and for farm need. For determining the optimal size of the equipment, it has to make a technical and financial analyse. The biogas valorisation case has to be compared with the reference case (treatment of manure in lagoons, with electricity bought from the public grid and local heat production in liquid fuel boiler).

Technical analyses of biogas use

An energy audit can determine the energy consumption for every farm. Using statistical data, it is possible to estimate the value of energy demand corresponding to animal unit. This parameter is variable with the climate, the farm processes and the level of automation. For a better simulation, a several number of type-days are used in the software (e.g. winter, spring, autumn or summer type-day). The global indicator to quantify the specific daily heat and power need is defined as a matrix

$$P_i = \begin{bmatrix} P_i^{1,1} & P_i^{1,2} & \dots & P_i^{1,j} & \dots & P_i^{1,z_{max}} \\ P_i^{2,1} & P_i^{2,2} & \dots & P_i^{2,j} & \dots & P_i^{2,z_{max}} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ P_i^{k,1} & P_i^{k,2} & \dots & P_i^{k,j} & \dots & P_i^{k,z_{max}} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ P_i^{24,1} & P_i^{24,2} & \dots & P_i^{24,j} & \dots & P_i^{24,z_{max}} \end{bmatrix} \quad q_i = \begin{bmatrix} q_i^{1,1} & q_i^{1,2} & \dots & q_i^{1,j} & \dots & q_i^{1,z_{max}} \\ q_i^{2,1} & q_i^{2,2} & \dots & q_i^{2,j} & \dots & q_i^{2,z_{max}} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ q_i^{k,1} & q_i^{k,2} & \dots & q_i^{k,j} & \dots & q_i^{k,z_{max}} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ q_i^{24,1} & q_i^{24,2} & \dots & q_i^{24,j} & \dots & q_i^{24,z_{max}} \end{bmatrix} \quad (1)$$

where P_i and q_i are the hourly power and heat demand corresponding of an animal unit and z_{max} is the maximal number of type-days. The hourly energy demand for the farm P_{farm} and q_{farm} can be calculated by multiplying the specific need with the animal number.

The potential of the biogas use can be calculated for each type of manure: hog, poultry, beef or dairy (Fulhage *et al.* 1993). Every type of manure presents specific pollution given by volatile solids content (a measure of the organic fraction of a sample, which can be burned at 450°F). The AD process efficiency is function of the manure composition. One can describe a function between the daily sample quantity produced by an animal and the biogas yield. The primary component of an AD system is the anaerobic digester, a waste vessel containing bacteria that digest the organic mater under controlled conditions to produce biogas. For the specific daily sample production of an animal, a digester volume is necessary. The different parameter values are listed in Table 1.

The biogas valorisation equipment is the engine. In addition, a biogas boiler can be installed. For a better management of the bio-fuel, a storage tank is necessary. Depending of the engine size a biogas yield can be burned. It will be produced a corresponding power and heat. If the thermal demand is not covered, the boiler burns another part of the biogas production. The flare destroys the rest. Figure 1 presents the diagram of the valorisation biogas equipment's system. Using this schema, figure 2 explains how biogas yield *b* can be used in order to cover the energy demand for 24 hours. If the biogas is not used, the farm has to buy electricity from the public grid and to produce heat in a liquid fuel boiler.
Considering the number of type-days for a year, it can calculate the annual energy substitution due of the biogas valorisation. Using the annual heat production, the

liquid fuel substitution is calculated with the efficiency of the boiler. A special part of the software is designed to calculate the annual CO_2 emission reduction, due to the valorisation biogas project.
A significant number of equations are used for describing the valorisation system. The most important is the biogas daily balance.

$$B = B_{engine} + B_{boiler} + B_{flare} \ \text{[Wh/day]} \tag{2}$$

Daily biogas production *B* has to be used or destroyed. A part of it is burned in engine B_{engine}, a part in boiler B_{boiler} and the rest is burned in flare B_{flare}. The hourly balance has to be closed by the biogas yield in/from storage.

$$b(t) = b_{engine}(t) + b_{boiler}(t) + b_{flare}(t) + b_{storage}(t) - b_{storage}(t+1) \ \text{[W]} \tag{3}$$

For the hourly biogas yield in storage tank and in flare, the possible ranges are:

$$0 \le b_{storage}(t) \le \hat{b}_{storage} \ \text{[W]} \tag{4}$$

$$0 \le b_{flare}(t) \le \hat{b}_{flare} \ \text{[W]} \tag{5}$$

The hourly biogas yield in engine is calculated with:

$$b_{engine}(t) = \frac{P(t)}{\eta_{engine}} \ \text{[W]} \tag{6}$$

where $P(t)$ is the engine hourly load and η_{engine} - the electrical efficiency of the engine. The recovered heat from the engine can be calculated as:

$$q_{engine}(t) = \frac{P(t)}{y} \ \text{[W]} \tag{7}$$

where y is the energy structure coefficient for engine (Athanasovici *and al.* 2000). If thermal need of the farm is superior of the recovered heat, the boiler can cover the difference.

$$\Delta q(t) = q_{farm}(t) - q_{engine}(t) \ \text{[W]} \tag{8}$$

Farm demand and technical restrictions limit the engine and boiler load.

$$P_{engine}(t) = \begin{cases} \hat{P}_{engine}, \text{ if } \hat{P}_{engine} < P_{farm}(t) \\ P_{farm}(t), \text{ if } k_{engine}^{min}\hat{P}_{engine} < P_{farm}(t) < \hat{P}_{engine} \\ 0, \text{ if } P_{farm}(t) < k_{engine}^{min}\hat{P}_{engine} \end{cases} \ \text{[W]} \tag{9}$$

$$q_{boiler}(t) = \begin{cases} \hat{q}_{boiler}, \text{ if } \hat{q}_{boiler} < \Delta q(t) \\ \Delta q(t), \text{ if } k_{boiler}^{min}\hat{q}_{boiler} < \Delta q(t) < \hat{q}_{boiler} \\ 0, \text{ if } \Delta q(t) < k_{boiler}^{min}\hat{q}_{boiler} \end{cases} \ \text{[W]} \tag{10}$$

where, $\hat{P}_{engine}, \hat{q}_{boiler}$ are the maximal load and $k^{min}_{engine}, k^{min}_{boiler}$ - the minimal load coefficient. If the export of the extra power is possible, the engine load would be maximal every time. The biogas yield in boiler is calculated with:

$$b_{boiler}(t) = \frac{q(t)}{\eta_{boiler}} \quad [W] \tag{11}$$

The CO_2 reduction is calculated based on the fossil fuel combustion. The biogas has to be burned, in flare or in valorisation equipment. The difference appears because, using the biogas for energy, a part of fossil fuel used for electricity and heat production will be saved. The hourly CO_2 reduction is calculated with:

$$R_{CO_2} = \lambda_e P(t) + \lambda_t \left(q_{engine}(t) + q_{boiler}(t)\right) \quad [kgCO_2/h] \tag{12}$$

where λ_e, λ_t represent the specific CO_2 emission for producing electricity and heat (RARE. 1998).

Financial analyses

In order to determinate the feasibility of the valorisation project, financial analyses is necessary. The value of payback period *PBP* is considered as criteria for deciding the opportunity of the project.

$$PBP = \frac{I}{V - C} \quad [year] \tag{13}$$

where *PBP* represents the payback period of the investments, *I* – investments for valorisation project, *V* – value of substituted energy and *C* – running and maintenance costs.

The investments in equipment correspond to the different parts of the valorisation schema.

$$I = I_{digester} + I_{storage} + I_{engine} + I_{boiler} \quad [\$] \tag{14}$$

The value of substituted energy is associated to the annual electricity and heat production through biogas valorisation. The farm will not buy the energy substituted by engine or boiler.

$$V = V_{power} + V_{heat} \quad [\$/year] \tag{15}$$

The running and maintenance costs are associated to the engine and to the boiler.

$$C = C_{engine} + C_{boiler} \quad [\$/year] \tag{16}$$

After statistical data (Demuynck *and al.* 1987), any farm biogas project needs subsidy to become feasible. Different forms are possible: the direct subsidy, the use of eco-taxes or the electricity export.
The algorithm for the optimisation software is presented in Figure 3. It follows the technical and financial analysis. The independent variables are $\hat{P}_{engine}$ and $\hat{q}_{boiler}$ and the target is to minimise *PBP* value.

Results

The software was applied for hog, poultry, beef and dairy farms. In order to verify the evolution of the results, is considered a specific range for the animal number. The values of different parameters used in software algorithm are presented in Table no. 2. The climate data are characteristic for a continental zone. Cordato (1998) has described the probable limits for the CO_2 taxes. The tariffs for electricity and liquid fuel are given for France. The initial assessment confirms that a valorisation biogas from manure project is not feasible without subsidies. Eco-taxes or extra-power export are used for reducing the authority subsidy's effort. The best results are obtained when direct subsidy is combined with extra-power export. Figure 4 presents the results of the analysis in these conditions. A project would be considered feasible if the PBP value will be less than 5 years.

For a hog farm (case a) with a subsidy rate 50%, the project cannot be accepted. About 12 000 units is the minimal size of the farm, in order to respect the PBP limit, for a subsidy rate 60%. For 70%, 6 000 units are enough for the demanded PBP value. Finally, any size of the farm (in the analysed range) would provide good financial results for the biogas valorisation projects.

Optimal size for the hogs farm is 10 000 units. The optimal capacity is 66 kWe for engine and 31kWt for boiler. Annual CO_2 reduction is 420 t/y. The direct subsidy has to be 290 th.$ (63% of total investment).

For poultry farms (case b), the projects become acceptable for 60% subsidy rate and 180000 units. Superior subsidy rates provide good financial performances for every size in the considered range. For a 200 000 units farm, the optimal size is 71 kWe for engine and 31 kWt for boiler. Annual CO_2 reduction is 447 t/y. The direct subsidy is 310 th.$ (58% of total investment).

Beef farms (case c) need important subsidy rates for biogas valorisation projects (but less absolute values). 300 units is the minimal limit for 70% subsidy rate and 150 units for 80%. For 500 units farm, the optimal size is 21 kWe for engine and 17 kWt for boiler. Annual CO_2 reduction is 145 t/y. The direct subsidy is 135 th.$ (66% of the total investment)

For dairy (case d), minimum 200 units with 80% subsidy rate is demanded for a good project. For 500 units farm, the optimal size is 16 kWe for engine and 12 kWt for boiler. Annual CO_2 reduction is 108 t/y. The direct subsidy is 173 th.$ (77% of the total investment).

Conclusions

The generated biogas from manure represents an important opportunity for energy valorisation. It would be used as fuel for engine and boiler. The recovered electricity and heat will improve the energy balance of the farm. The size of the equipment has to be optimised, in order to obtain the requested financial efficiency. A biogas valorisation project for a farm cannot be feasible without an external aid. Direct subsidy combined with extra-power export represents the best solution for a biogas valorisation project. Once the biogas plant sized, the optimising software will provide the best repartition of the bio-fuel. The liquid fuel price and the electricity tariff will affect the hourly distribution of the biogas yield. Consultancy engineers for feasibility studies can use the software.

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Tables

Table 1. List of specific parameters value for different type of manure (Fulhage et al. 1993).

Specific Parameters	Unit	Hog	Poultry	Beef	Dairy
Volatile solids production	kg/day/cap	0.32	0.02	2.27	4.31
AD process efficiency	%	49	56	41	31
Biogas yield for VS unit destruction	$Nm^3/kgVS$	0.75	0.54	0.94	0.48
Biogas yield for animal unit	$Nm^3/day/cap$	0.12	0.006	0.88	0.64
Digester capacity for VS destruction	$kgVS/day/m^3$	2.24	1.92	5.93	5.93
Digester volume	m^3/cap	0.14	0.01	0.38	0.73

Table 2. List of parameters' value for numerical simulation.

Specific Parameters	Unit	Range	Used for calculation
Min. load coefficient for engine	%	20-30	30
Min. load coefficient for boiler	%	10-20	20
Energy structure coefficient	-	0.7-1.2	1
Engine efficiency	%	20-30	25
Boiler efficiency	%	80-92	90
CO_2 emission for electricity production	$kgCO_2/kWh$	0-0.6	0.46
CO_2 emission for heat production	$kgCO_2/kWh$	0.1-0.3	0.2
Tariff of bought electricity	c$/kWh	4-10	7
Tariff of exported electricity	c$/kWh	2-8	4.2
Tariff of liquid fuel	c$/kWh	1-2	1.5
CO_2 eco-tax level	$/tonne	100-200	100

Figures

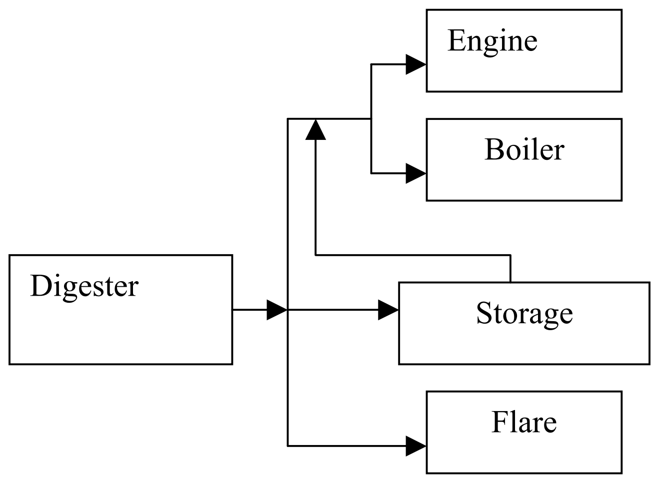

Figure 1. Diagram of the valorisation biogas equipment's system

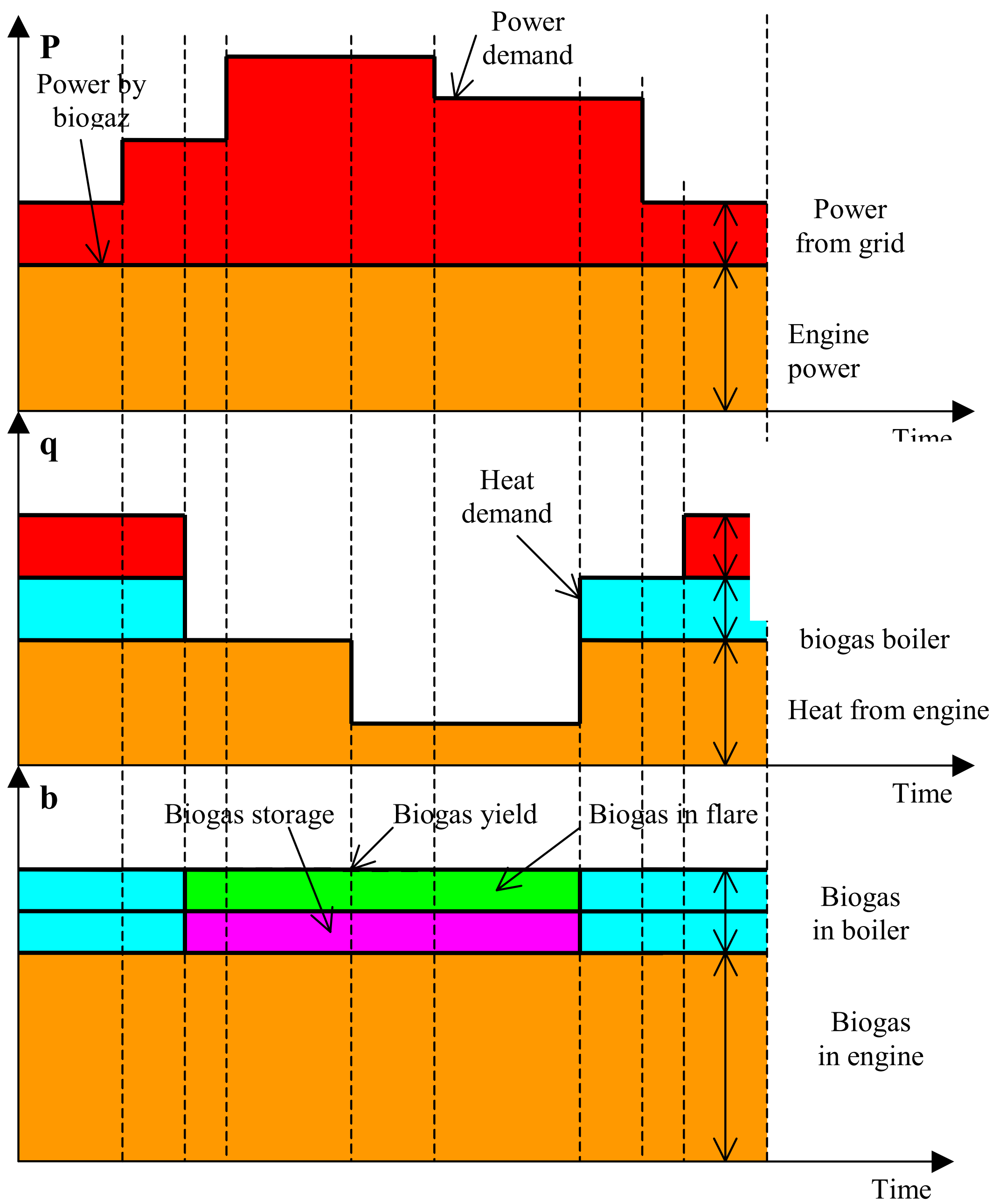

Figure 2. Optimal biogas use in engine and boiler for covering a part of daily power and heat demand of a farm

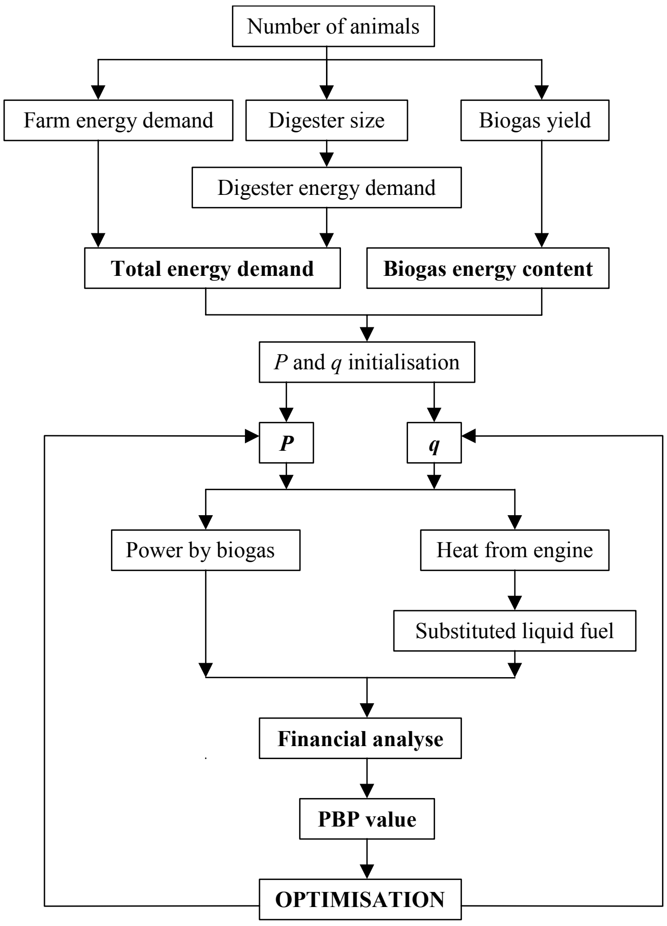

Figure 3. Optimisation algorithm for sizing the biogas engine and boiler

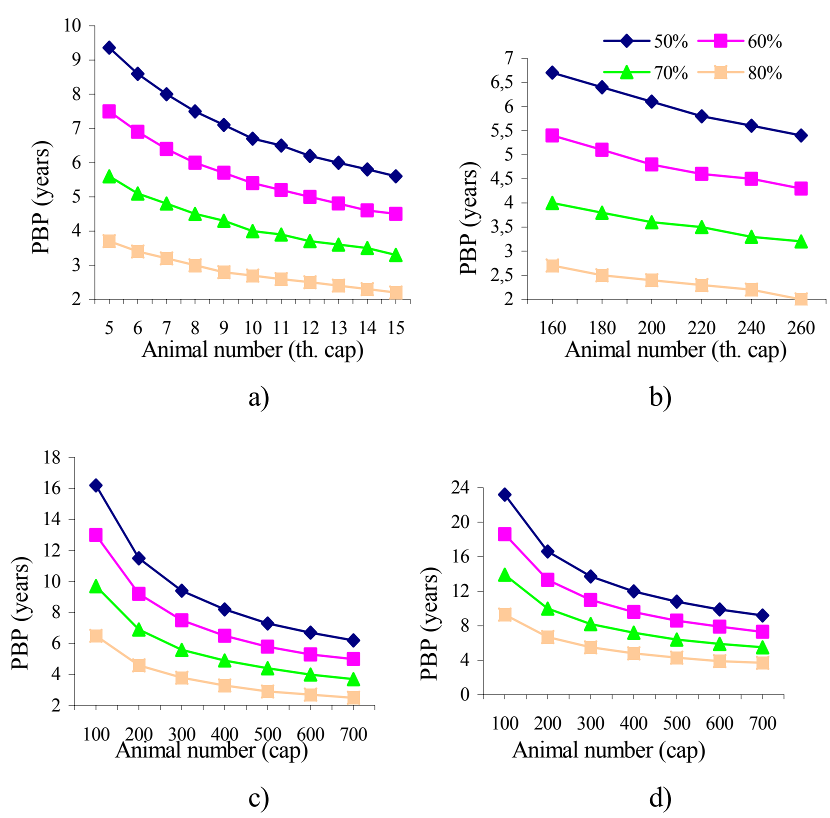

Figure 4. PBP variation with the farm size for different subsidy rates and extra-power export (a-hog, b-poultry, c-beef, d-dairy)