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# Emergy analysis of energy transition from coal to renewable at chicken farm

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Abstract

The paper presents an emergy analysis of the poultry farm regarding shifting energy sources from fossil fuels to biomass generated onsite in broilers and hen eggs rearing systems. It has been found that the manure produced on the farm has sufficient energy potential to replace the currently used energy carriers, both for heating and electricity supply. Replacing the currently used conventional energy resources with chicken manure will increase the emission charges. However, implementation of low-emission combustion techniques can help with reducing the emissions. Emergy analysis showed that for the conventional energy mix used in the farm, the Renewability Index (REN) is 0.5797, the Environmental Loading Ratio (ELR) is 171.49 and the Emergy Yield Ratio (EYR) has a value of about 1. If energy carriers are replaced by chicken manure, the REN may increase by 6.19% and the ELR may decrease by 6.11%. These relatively small changes should be considered in the context of the large scale of chicken production in Poland.

## Introduction

Modern poultry farming should be focused on providing high quality food products in accordance with the principles of sustainable development as a combination of the economic, social and environmental aspects. In fact, poultry industrial-scale production, including chicken farming, is based on providing inexpensive items for consumers whilst maximizing profit for producers. This is accompanied by optimization of the environmental costs of livestock operations, enforced by increasing restrictions to reduce on limiting pollution and waste loads of the production [1].

The issue of sustainable chicken livestock farming is important given the successively increasing trends of the global consumption and production of hen eggs and poultry meet in last decade. Poultry farming in the world, including Europe, is constantly growing. For instance, Poland, the leading European poultry producer, has a chicken population estimated at over 176 million, corresponding to a volume of chicken manure of around 4.49 million tons per year. European Union (EU) produced about 7 million tonnes of chicken meat in 2010, while in 2020 it was already 11 million tons [2]. The growing scale of production contributes to higher profitability, but at the same time it increases the hazard to the natural environment leading to its degradation [3].

Due to the considerable concentration of birds in chicken farms, the problem of identifying and reducing the negative effect of chicken production on the environment is becoming increasingly important. The relations between the environment and production should be discussed considering two aspects. The first is associated with the consumption of renewable and non-renewable resources, obtained directly from nature or purchased. The second aspect is related to the generation of pollution and increased environmental risk caused by sewage, waste, odours, noise as well as spread of animal diseases.

The specific stages of farm operation lead to the consumption of considerable amounts of resources, among which energy carriers are a significant item. The level of energy consumption depends on the climate zone and the type and technical condition of farm equipment. Energy consumption on chicken farms is mainly related to heating, ventilation and lighting, energy use for distribution, forage preparation, egg collection and sorting, as can be seen in Table 1.

*Table 1: Indicative levels of daily energy consumption of essential activities on chicken farms in Italy [4]*

| Activity | Estimated energy use | | |
|---|---|---|---|
| | Unit | Broilers | Laying hens |
| Local heating | Wh/bird | 13-20 | - |
| Feeding | Wh/bird | 0.4-0.6 | 0.50-0.80 |
| Ventilation | Wh/bird | 0.10-0.14 | 0.13-0.45 |
| Lighting | Wh/bird | - | 0.15-0.40 |
| Egg production | Wh/egg | - | 0.30-0.35 |

As reported in [4], electricity consumption on chicken farms depends on the intensity of rearing. Annual average electricity consumption for broiler production in France is determined to be in the range from 9.4 to 20.3 kWh/m2 of the broiler house surface. According to [4], chicken house ventilation and lighting are the dominant items, responsible for respectively 48.1% and 32.5% of total electricity consumption.

There are many environmental issues related to poultry production, however the most serious inconvenience is caused by generation of huge amount of chicken manure. The quantity of manure excreted depends on the feed consumption, its quality, water, the age of the birds and their productivity. In general, the amount of poultry produced by laying hens may vary from 100 to 150 g/day/bird, and in the case of broilers, from 50–160 g/day/bird [5,6]. In Poland which is a leading poultry producer in Europe, the volume of chicken manure was assessed as 4.49 million tons per year [7,8]. Another environmental problem of chicken production is bird losses that generate a fairly large amount up to several percent of total waste from big-scale chicken farms.

Nowadays in Poland chicken manure is mainly used as a mineral fertilizer or a substrate for mushroom farming. Using huge amount of chicken manure as an organic fertilizer results in environmental degradation due to over-fertilization and atmospheric emissions of hazardous substances such as dust or ammonia $NH_3$. Since ammonia emissions generated during chicken manure land spreading is several dozen times greater than emissions from combustion, it is worth considering alternative poultry manure treatment: directly on the farm and in line with a sustainable approach to environmental protection [7]. One of the solutions for sustainable chicken manure treatment is using it for generation of useful energy such as heat or electricity. Due to its unstable and unique physicochemical properties, energy applications based on chicken manure is still not common and rather rarely used. The spectrum of technologies that in this case can be applied is very wide, however the most technologically advanced are the processes of combustion and co-combustion of chicken manure. Regardless of the technology considered, the use of chicken manure for efficient energy production requires that the substrate is properly prepared for the process, at least by drying. Alternative use of chicken manure should always be subject to detailed environmental and economic analysis.

One method to assess the environmental impact of production is emergy analysis [9]. The emergy analysis and the calculation of emergy indicators are mainly aimed at determining the degree of environmental usage in a given activity and its environmental sustainability. Emergetic calculation as well as the emergetic monetary equivalent can be applied to any kind of production. Emergy approach is the most commonly used in the analysis of agricultural production, mainly crop production but also livestock production or in the assessment of the environmental impact of fish farming [10]. This method is also used to evaluate various types of restoration activities for greenfield restoration. This is due to the fact that in agricultural production and farming activities, the degree of environmental use is relatively high. Then, the emergy indices are a good measure to compare the degree of environmental pressure across different types of production, including both: conventional and environmentally friendly.

In the literature emergy analysis of breeding and production of poultry meat and eggs can be found, however they mostly concern small-scale farms. In [11], two organic poultry rearing systems in China were compared: a family-operated farm with a population of 100 birds and a farm of 2,000 chickens with orchard-based free-range system. Presented results show that the emergy yield ratio (EYR) of both cases were close to unity, respectively 1.10 and 1.11, which means that there is almost no additional use of local resources. In turn, it was noted that the environmental loading ratio (ELR) was more variable between the two systems, concluding that the family-operated organic rearing system (ELR = 3.10) exerts less pressure on the environment compared to the orchard-based field rearing system (ELR = 3.44). These breeding systems were compared with two Italian ones, an organic system with 1,000 free-range birds and a conventional system with 15,600 chickens detailed in [12]. For the conventional Italian system, the emergy-based indicators were EYR = 1.19 and ELR = 5.21, while for the organic system they were determined to be 1.51 and 2.04, respectively. Of the systems analyzed, the Italian organic grassland-based rearing system was found to be the most beneficial in terms of environmental load and overall sustainability. The system was considered as the closed to the real practise of organic production, because of more efficient local resources usage.

In [13] a partial-organic duck farm with a stocking rate of 12,500 ducks was analyzed. The highest energy consumption was associated with purchased feed and service. Production was characterized by emergy indicators of EYR of 1.01 and ELR of 8.85. It has been also observed that good economic performance obtained by the scale effect, intensity and efficiency of production, is not in a sustainable pattern. The paper [14] presents emergy analysis of egg production referred to 100 laying hens per year. The analysis determines the emergy demand of production inputs, the total energy consumption per unit of the product and solar convertibility. The energy consumption of layer houses was evaluated as 3.99E+20 in sej/ha/yr, however no additional emergy indicators were specified. Performed literature research has shown, that there is a lack of detailed emergy analyses for intensive poultry farming, with several hundred thousand birds per year. These farms, under European conditions, are both primary suppliers of poultry meat and eggs to the market and make intensive use of environmental resources.

The aim of this paper is to perform the emergy analysis for large-scale chicken farm and to determine the use of emergy in particular components of production. Another objective of the analysis is to determine the potential for reducing production pressure on the environment due to changes in the energy management of the plant by replacing the current energy carriers based on fossil fuels with energy generated from dried chicken manure produced directly on the farm.

# Materials and methods

## System description

The input data for the research was taken from a chicken farm located in the south-western Poland, in the Opolskie province. The analysed farm is a producer of broilers for meat and laying hens reared for eggs. Unproductive hens are also used for meat production. The farm consists of 14 henhouses, each with an area of 860 $m^2$. It forms an assembly with two houses joined by a connector building, see Figure 1.

Laying hens are kept in seven houses (1 to 5, 13, 14). Buildings 1 to 5 are equipped with a multi-tier battery-cage system and are not heated. Stocking density of laying hens in cage system varies from 20 to 23 thousand birds. The houses labelled as 13 and 14 contain 12,500 laying hens each and are operated as non-cage free range system of total area of 2.4 ha. They are equipped with a multi-level system of nest boxes and roosting perches. They have no heating installation. There are small amounts of sawdust applied as the litter in these building. Additionally, the farm has two henhouses for hatching chickens (houses no. 11 and 12) of 24 and 23 thousand birds populations with system of floor and litter breeding. In the broiler houses (6 to 10) a conventional litter system is used. Each house is designed for 15,000 chickens in a single breeding cycle.

All poultry houses have automatic feeding and watering facilities and are equipped with ventilation systems with air inlets integrated with roof and wall fans. Henhouses are equipped with automatic removing manure facility. The manure mixed with litter in broiler houses is removed manually with backhoe loader. Broiler houses are heated with open combustion heaters supplied with heating oil. Hatching housing are heated by coal-fired water boilers. The auxiliary infrastructure of the farm are: drain-less tank for domestic sewage, machinery room, straw warehouse, garage, packaging warehouse, waste disposal warehouse, water well, hydrophone, utility rooms and office and staff facilities. The analysed farm employs 18 people, including 10 people related to the operation of poultry houses.

The production of broilers and the rearing of laying hens begins with the purchase of day-old chickens from hatchery. Chicks for broilers are then placed directly to broiler houses for 42 days rearing cycle (six consecutive production cycles per year) until they reach a final weight of about 2.4 kg. There is a disinfection break after each cycle. The slaughter of the broilers takes place outside the farm. In case of laying hens, chicks are kept in laying hens rearing houses for about 16 weeks. Two full chick rearing production cycles take place during the year. After that period they are moved to laying hens houses where they stay for about 62 weeks. The eggs produced in laying hens houses are collected on a conveyor belt and delivered to warehouses. After the end of the cycle and liquidation of the flock, a technical break follows, during which the remaining manure, remains of feeder other after production wastes are removed. Chosen production data of the farm are presented in Table 2.

In the analyzed farm the total volume of chicken manure produced annually is around 8,074 Mg, mostly generated from laying hens systems. Energy consumption profile is changing in time, both during the day and particular seasons of the year. Electricity is used for ventilating poultry houses, lighting, feeding systems, watering, removing manure, and collection of the eggs. The chosen electricity demand data is presented in Table 2. The total electricity consumption is 865,000 kWh, which gives the mean unitary consumption of 11.72 Wh/bird/day (regarding all birds on the farm).

Heat demand of the farm is changing according to the breeding cycle and the season. In the investigated poultry production, the annual demand for thermal energy in fuel (coal and heating oil) for heating hen houses is 4.25E+06 MJ. Five broiler houses are heated with fuel oil using six heaters with a capacity of 80 kW, five of 100 kW and four of 160 kW. The annual oil fuel demand is 52,370 kg. There are also four coal-fired boilers installed on the farm: three 160 kW boilers and one 140 kW boiler. Only two henhouses for laying chicks are heated with coal, and the consumption is 84,100 kg per year.

*Table 2: Production data of the analyzed chicken farm*

| Item | Unit | Production data |
|---|---|---|
| Rearing cycles volumes: | | |
| - broilers/cycle/house | thousand | 15 |
| - laying hens/cycle/house | thousand | 22-24; 20; 12.5a) |
| Total number of birds per year: | | |
| - broilers | thousand | 75 |
| - laying hens | thousand | 131 |
| Henhouse area: | m2 | 860 |
| Birds density: | | |
| - broilers/cycle | bird/m2 | 17.4 |
| - laying hens - cage system | bird/m2 | 9 |
| - laying hens - free range system | bird/m2 | 0.075 |
| Production: | | |
| - final average weight of broiler | kg | 2.4 |
| - broiler meat | tons/year | 1,080 |
| - hens meat | tons/year | 275 |
| - average eggs number/laying hen | total/year | 215 |
| - average annual mortality rate | % | 3.5 |
| Feed consumption rate: | | |
| - broiler chickens | g/bird/day | 60 |
| - broilers | g/bird/day | 119 |
| - laying hen chickens | g/bird/day | 60 |
| - laying hens | g/bird/day | 112 |
| Chicken manure production: | Mg/year | 8,074 |
| Electricity consumption: | kWh/year | 865,000 |
| Fuel consumption: | | |
| - heating oil | kg/year | 52,370 |
| - coal | kg/year | 84,100 |

a) free range houses

The total demand of the farm for chemical energy of both for power and heat is equal to 13,829 GJ/year, assuming efficiency of heat production from oil as 0.85, efficiency of heat production from coal as 0.75 and electricity production in conventional power plant as 0.35.

## Problem formulation and methods

One of the ways of reducing the impact of the analyzed production on the environment is associated with the limitation or complete substitution the heating of poultry houses with the non-renewable fuels, i.e. coal and heating oil by other measures. Such possibility is feasible as a result of the valorization of pre-dried or dried chicken manure, which can be used as fuel. This possibility has been reported in a number of studies [15,16,17]. In the analysis conducted within the presented research, the substitution of fossil fuels was based on two alternatives of transition: using dried manure only for heat generation in a fluidized boiler (Scenario B) or using dried manure for heat and electricity in Organic Rankin Cycle system (Scenario C).

The current, only fossil-fuel-based energy system is described as Scenario A.

## Energy potential of proposed poultry manure valorization

The amount of energy Ed used for water evaporation from manure depends on dryer efficiency resulting from specific heat and electricity demands of drying process can be calculated as:

$$E_d = B_w(q + e) \qquad (1)$$

where: $E_d$ - the amount of evaporated water, (kg), $q$ - specific heat demand for drying, 0.9 kWh/kg of evaporated water, $e$ - specific electricity demand for drying, 0.08 kWh/kg of evaporated water [18].

Within the applied approach, the energy $q_s$ needed to remove 1 kg of water from the raw manure, related to energy of the fuel used for heat and electricity generation, is expressed as follows:

$$q_s = \begin{cases} \frac{q}{\eta_{th,b}} + \frac{e}{\eta_{el,E}} & heat \\ \frac{q}{\eta_{th,ORC}} + \frac{e}{\eta_{el,ORC}} & heat\ and\ electricity \end{cases} \qquad (2)$$

where: $\eta_{th,b}$ - thermal efficiency of the boiler fuelled with manure, $\eta_{th,b}$ = 0.80; $\eta_{el,E}$ - electrical efficiency of system power plant, $\eta_{el,E}$ = 0.40; $\eta_{el,ORC}$ - thermal efficiency of ORC unit fuelled with manure, $\eta_{th,b}$ = 0.70; $\eta_{el,ORC}$ - thermal efficiency of ORC unit fuelled with manure, $\eta_{el,ORC}$ = 0.18 [19].

For the assumed values of specific energy demand as well as efficiency of energy conversion, the total energy needed to remove 1 kg of water from the raw manure is equal to: 1.33 kWh for Scenario B and 1.73 kWh for Scenario C.

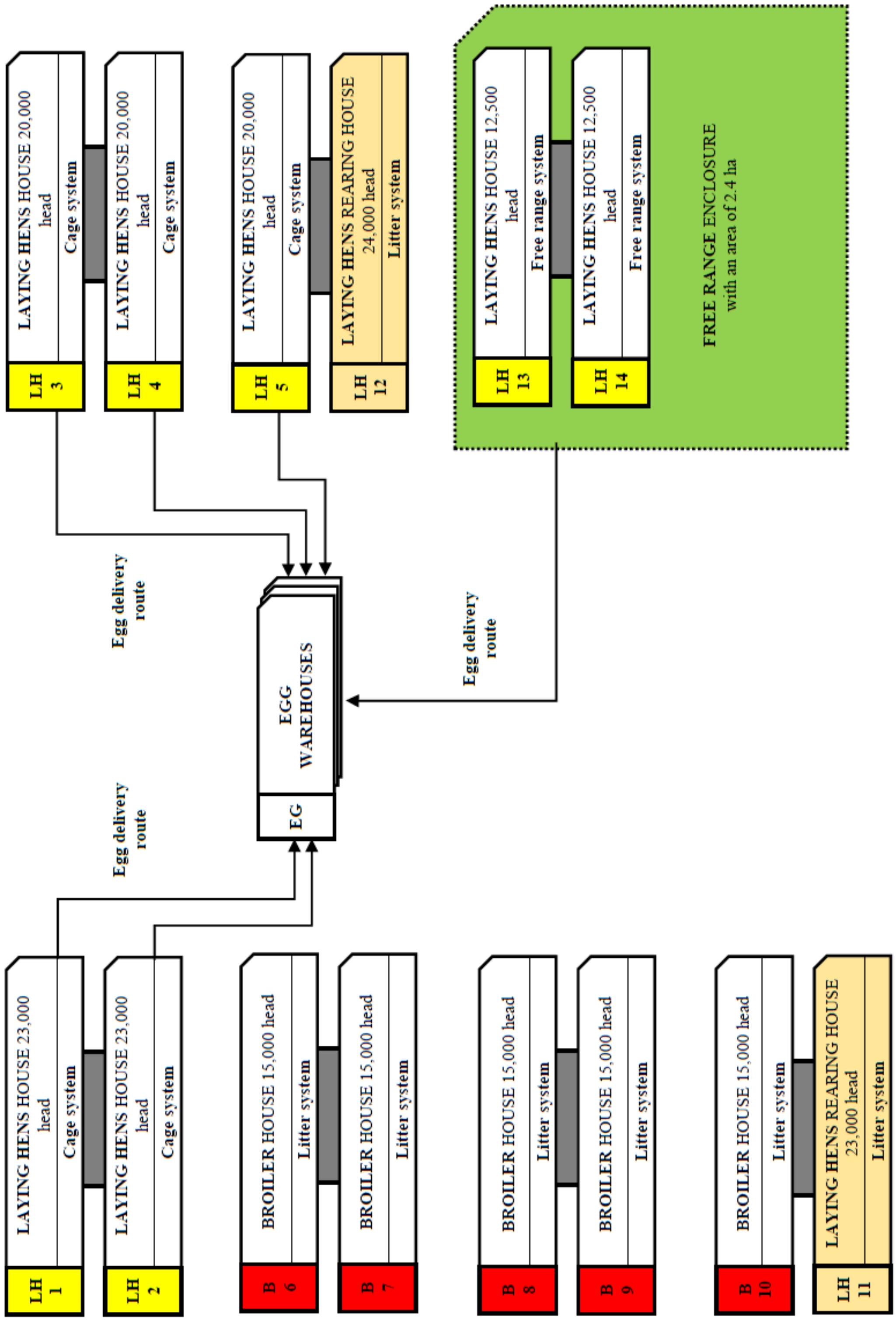


*Figure 1: Structure diagram of poultry farm system*

The moisture content of the raw chicken manure is in the range of 50–70%, and its calorific value in this condition is low, from 2 to 6 MJ per kg of raw manure.

The moisture content of the raw chicken manure is in the range 50-70%, yielding low calorific values, from 2 to 6 MJ/kg. These values depend mainly on the rearing system (cage, litter, free range) and on the degree of manure dryness before it is removed from the poultry house [7]. On the basis of the analysis, moisture content in the raw manure can be assumed as 71% following research performed on a farm [17]. It can also be assumed that the manure is dried (outside the poultry house) to a moisture level of 35% of its weight. Through this process, its calorific value increases to about 8 MJ/kg of manure. The amount of manure after drying is derived from the formula:

$$B_{Mf} = B_{Mb}\left(1 - x_b + x_f \frac{1-x_b}{1-x_f}\right) \quad (3)$$

Considering the initial moisture content $x_b$ = 0.71 and the final content $x_f$ = 0.35, an amount of $B_{Mf}$ = 3,590 Mg of fuel with theoretical energy potential of 28,720 MJ is obtained.

Energy balance of poultry houses, requires heat generated by the birds to be taken into account. In accordance with the literature data, the thermal power generated during the poultry - the demand in the rearing process is 12.12 W per broiler [20]. Other reports contains data in the range from 1.0 to 17.1 W/broiler depending on the bird's age [21].

Under the assumption of the mean annual heat flux generated by a hen at the level of 10W, the total energy output generated by poultry per year is about 63E+06 MJ. This means significant amounts of heat, requiring intensive ventilation, in particular in summer. In the period of scorching heat, it is also recommended to cool the circulating air. The output of large amounts of heat accompanying the process of ventilating henhouses with air at a temperature of about 20 °C and a humidity of 40–60%, offers the potential for the application of the air stream for dry manure. There are existing technical solutions that apply air derived from ventilating poultry houses in the process of drying manure. It is possible to dry all the manure removed from the poultry houses on an ongoing basis, to a moisture level of 20%. Having the opportunity to dry the manure, the energy obtained in the dry manure can be estimated at 28.7E+08 MJ. Theoretically, it makes it possible to cover the energy needs of the analyzed production. In this process, the technical solution described in [7] can find application, which applies a fluidized boiler or/and Organic Rankin Cycle system. A separate issue is associated with the economic aspects of the investment that need to be undertaken to modernize the energy management system in the farm.

Similar to [7] and assuming energy generation efficiency for Scenario C (applying ORC system), the total demand for energy both for power and heat is equal to 2.18E+08 GJ/year (including coal and fuel oil and replacement of liquid fuel with solid fuel).

## Environmental fees

Any economic activity related to poultry farming involves negative impact on the environment, in particular the emission of large amounts of pollutions discharged into air, soil and water [22]. Therefore, the operation of a poultry farm involves environmental fees depending on the: (a) pollutants emissions into air form the poultry rearing systems, (b) pollutants emissions form heat sources (c) water consumption, (d) sewage disposal, and (e) waste generation. The direct use of poultry manure as energy carriers can significantly affect the first two of the listed fee components related to the air contamination.

Currently, laying hens are reared in two systems: a cage one with a conveyor belts for excrements removal and free-range with litter as bedding material. The hatching chickens as well as broilers are reared in a cage-free systems with litter. The unit fee for gas and dust emissions from the listed four systems are 1.79, 4.26, 3.80 and 3.13 USD/100 birds, respectively. Taking into account the number of poultry for the individual systems (see Fig. 1 and Tabel 3) and the applicable fee rates, the environmental fees for the individual systems are equal to: 4,748.40 USD for laying hens and chickens, and 2,347.50 USD for broilers as presented in Tabel 3.

*Table 3: Environmental fees related to emissions from the rearing systems - current state*

| Breading | Farming system | Fee rate[a)] | Total number of heads in system | Envir. fee |
|---|---|---|---|---|
| | | USD | thousand | USD |
| Laying hen | Cage with belt faeces removal | 1.79 | 106 | 1,897.40 |
| Laying hen | free-range/litter | 4.26 | 25 | 1,065.00 |
| Chickens | cage-free/litter | 3.80 | 47 | 1,786.00 |
| Broiler | cage-free/litter | 3.13 | 75 | 2,347.50 |
| | | | Total: | 7,095.90 |

a) per 100 birds

The on-farm application of manure combustion technology requires pre-drying of the fuel before feeding it into the combustion chamber. The use of a mechanical manure pre-drying system is rewarded with lower fees in the legal system. The fee for using the manure draying in free range cage-system is 1.45 USD (instead of 4.26 USD), as well as 2,10 USD (instead of 3.80 USD) and 1.45 USD (instead of 3.13 USD) for the litter systems for chickens and broilers respectively. The National legislation does not permit a fee reduction for a laying hens cage system with mechanical drying. Finally, manure pre-draying gives a reduction in the environmental fee to 3,204.60 USD for laying hens and chickens rearing systems, and 1,087.50 USD for broilers as can be see in Tabel 4. The total environmental fee related to emissions from the rearing process decrease by approx. 39.5% as a result of drying the faeces compared to the current state.

*Table 4: Environmental fees related to emissions from the rearing systems - target state*

| Breading | Farming system | Fee rate[a)] | Total number of heads in system | Envir. fee |
|---|---|---|---|---|
| | | USD | thousand | USD |
| Laying hen | Cage with belt faeces removal | 1.79 | 106 | 1,897.40 |
| Laying hen | free-range/litter | 4.26 | 25 | 362.50 |
| Chickens | cage-free/litter | 3.80 | 47 | 944.70 |
| Broiler | cage-free/litter | 3.13 | 75 | 1,087.50 |
| | | | Total: | 4,292.10 |

[a)] per 100 birds

The second source of environmental charges is due to the gas and dust emissions of the combustion processes realized in coal- and oil-fired boilers. The total environmental fee TEF may be calculated following the equation Eq. 4:

$$TEF = \sum_i FR_i \cdot CEI_i \cdot B_c + \sum_i FR_i \cdot CEI_i \cdot B_o \qquad (4)$$

where: *i* - pollutant number; *FR* - fee rate, (USD/kg); *CEI* - coal mission index, (kg/Mg); $B_c$ - annual coal consumption, (Mg/year); *OEI* - oil mission index, (kg/m$^3$); $B_o$ - annual oil consumption, (m$^3$).

The emission indexes are determined by the fuel properties, including sulphure and ash contents, and recalculated following factors according to the National Emission Inventory [23]. A summary of the feed rates and emission indexes quoted for various pollutants is presented in Table 5. The total environmental fee due to the exhaust emissions from heating equipment, at approximately 460 USD, is relatively low compared to the fee related to emissions from livestock facilities, and is therefore not a meaningful item in the company's financial statement.

*Table 5: Environmental charges related to coal and oil combustion on the farm - current state*

| Pollutant | Fee rate | Coal Emission Index | Oil Emission Index | Envir. fee |
|---|---|---|---|---|
| | USD/kg | kg/Mg | kg/m$^3$ | USD |
| $SO_2$ | 0.13 | 12.8[e)] | 0.0017[g)] | 139.95 |
| $NO_2$ | 0.13 | 3.2 | 2 | 51.20 |
| CO | 0.03 | 10 | 0.57 | 26.30 |
| $CO_2$ | 0.07[d)] | 2130 | 2700 | 24.32 |
| TSP[a)] | 0.09 | 24[f)] | 0.34 | 183.57 |
| BC[b)] | 0.37 | 0.24 | 0 | 7.47 |
| BaP[c)] | 96.55 | 0.0032 | 0.00026 | 27.55 |
| | | | Total: | 460.36 |

[a)] Total Particulate Matter
[b)] Soot
[c)] Benzo/a/Pyrene
[d)] USD/kg
[e)] Sulphur content in coal, assumed as 0.8%
[f)] Ash content in coal, assumed as 12%
[g)] Sulphur content in oil, assumed as 0.1 mg/kg

Emission indexes form poultry manure combustion are not determinable based on the National Emission Inventory Database [23]. However, the Commission Regulation (EU) 592/2014 provides emission limits for sulphur dioxide $SO_2$ (50 mg/Nm$^3$), nitrogen oxides as $NO_2$ (200 mg/Nm$^3$), and particulate matter TSP (10 mg/Nm$^3$) that have to be met for an on-farm poultry manure combustion plant. These emission limits are met by fluidised bed boilers combined with CHP technology for poultry manure incineration [24], where the concentrations in the exhaust gas for individual compounds are $SO_2$ = 18.4 mg/Nm$^3$, NOx = 167 mg/Nm$^3$, PM = 2.7 mg/Nm$^3$ as well as CO = 5.3 mg/Nm$^3$. Taking into account the physicochemical parameters of the chicken manure for combustion purposes and assuming the oxygen concentration in the flue gases generated by the FBC boiler by approximately 5.5%, the Poultry Emission Indexes are at levels stated in Table 6. In summary, the environmental fee will be about 318 USD as a result of the implementation of on-site manure incineration technology and is at a level comparable to the heating technology used to date.

*Table 6: Environmental charges related to coal and oil combustion on the farm - target state*

| Pollutant | Fee rate | Poultry Emission Index | Envir. fee |
|---|---|---|---|
| | USD/kg | kg/Mg | USD |
| $SO_2$ | 0.13 | 0.067 | 31.07 |
| $NO_2$ | 0.13 | 0.604 | 281.98 |
| CO | 0.03 | 0.019 | 2.07 |
| $CO_2$ | 0.07 | n.a. | - |
| TSP[a)] | 0.09 | 0.010 | 3.16 |
| BC[b)] | 0.37 | n.a. | - |
| BaP[c)] | 96.55 | n.a. | - |
| | | | 318.28 |

[a)] Total Particulate Matter
[b)] Soot
[c)] Benzo/a/Pyrene

Considering the environmental aspects of direct on-farm manure combustion, it should be noted that the bottom ash can be sustainably recycled for soil enrichment or as a phosphorus- and calcium-rich additive for poultry feed [25]. Fertiliser from ash is more stable and sterile due to the absence of pathogenic microorganisms, and the minerals it contains have greater availability to plants compared to raw poultry litter. Furthermore, ash-derived fertiliser is also much easier to use, transport and market than natural fertilisers.

Finally, it should be mentioned also, that the emergy analysis ignores avoided off-farm emissions due to transport and fertiliser application. The effect of agricultural areas over-fertilisation is to create an excessive environmental load, through redundant migration of nitrates and phosphates into water bodies, or high uncontrolled emissions of $NH_3$, NOx, $N_2O$ and odours into the air [15,22].

## Emergy analysis

Emergy analysis takes into account all the components that affect a given activity, including energy and monetary aspects. According to the standard approach [9], the amount of emergy depends on direct or indirect demand for exergy of solar radiation during generating given product or service. The emergy of a given independent component (product or service) can be derived from the equation:

$$E_m = \begin{cases} RF \cdot E_x \cdot \tau & renewable \\ (1-RF) \cdot E_x \cdot \tau & nonrenewable \end{cases} \quad (5)$$

where: $E_m$ - amount of emergy, (seJ); $E_x$ - amount of exergy, (J); $\tau$ - solar transformation, (seJ/J); $RF$ - renewability factor.

A number of products and services are characterized by high complexity and the involvement of numerous intermediate components, including monetary flows. Many processes under analysis contains number of interactions and different production methods or technologies. Nowadays, for such cases, literature reports monetary method of analysis [26], where emergy is derived from the formula:

$$E_m = \begin{cases} RF \cdot f \cdot UEV & renewable \\ (1-RF) \cdot f \cdot UEV & nonrenewable \end{cases} \quad (6)$$

where: $f$ - inpute data, (kg) or (USD); $UEV$ - specific convertibility of the particular input data, (seJ/kg) or (sej/USD).

In both approaches (exergy- and monetary-based) total amount of emergy $E_{m,t}$ of particular components (inflows), is a sum of renewable emergy $E_{m,r}$ and nonrenewable emergy $E_{m,nr}$ as follows:

$$E_{m,t} = E_{m,r} + E_{m,nr} \quad (7)$$

Overall emergy amount derived for analysed poultry rearing system is a sum of emergy of particular *i* th components of the systems:

$$E_{m,overall} = \sum_i E_{m,t_i} \quad (8)$$

The concept of emergy calculation is similar to the determination of the thermoecological cost of a product [27], but, takes greater account of the environmental impact. Additionally, the current studies include details of whether a given element of emergy originates from renewable or non-renewable sources. The first category includes solar radiation, water, wind, often human labor and, in part, agricultural products. Common materials derived from non-renewable sources include: fossil fuels, chemicals or building materials. Often a factor is introduced, the so-called renewability factor (*RF*), which determines the degree of renewability of certain materials or services in terms of a fraction or as a percent ratio. The values of the factor, although they relate to practically the same material/service, may differ significantly in specific cases. This may result from local conditions of production, the ratio of local sources or purchased ingredients, as well as can depend on the assumptions that are made in a specific case. For instance, human labor investigated in [28] was assumed to be a service with sustainability factor of 10%, whereas in [29] this level was assumed at 5%, as the remaining proportion of the labor necessary to complete the task was considered as a purchased service with non-renewable characteristics. In [13] the sustainability of human labor was assumed at the level of 90%, regardless of whether it is work performed using the local resources or a purchased service. These differences mean that despite the same total emergy related to a given production, the ratios of the renewable and non-renewable parts may offer different results. As a consequence, different values of emergy-based indicators are gained and the comparison of various production methods and their effect on the environment is impeded.

Table 7 contains a summary of all the essential ingredients of importance in the analyzed production. The table summarizes the magnitude, assumed level of sustainability and solar transformation, specific monetary values, total monetary values and as well as total emergy. The table also contain details of emergy determined with regard to the given components, distinguishing between the renewable and non-renewable parts. The conversions took into account the Polish monetary equivalent (National Emergy Money Ratio) of 2015 named *P1*, equal to 6.09E+12 seJ/USD [30].

Some of the most common emergy-based indicators include *ELR* and *EYR* [31,32,33]. The first is defined as the ratio of total non-renewable emergy use to renewable emergy. This forms a measure of the environmental load generated by a given type of production and the technologies applied in it. The other one, EYR, which provides an insight into the net benefit of production, is expressed by the ratio of the total emergy (*Y*) expended in production to the total emergy in the components purchased on the market for the purposes of this production. Human labor and services are also paid in these components. The aim is to obtain the lowest *ELR* value and the highest – *EYR* value in the production systems.

## Results and discussion

The emergy flows and its changes due to substitution of the current energy resources with a fuel derived from poultry manure are presented in Figure 2. The symbols used in the figure are consistent with emergy systems code proposed by Odum [9].

Nearly all production materials are purchased off-farm and staff is employed on a contract basis. All prices and salaries are quoted in USD, at an average 2016 USD/PLN exchange rate of PLN 3.82. The data presented in Table 7 show that the largest items are feed and feed additives, in terms of cost and emergy. In total, its emergy is equal to 1.52E+19 seJ. Human labour costs have an emergy equivalent of 1.93E+18 seJ. The energy carriers have a total emergy value equal to 1,10E+18 seJ, and the emergy assigned to the average annual maintenance expenses of buildings and equipment is equal to 5.76E+17 seJ.

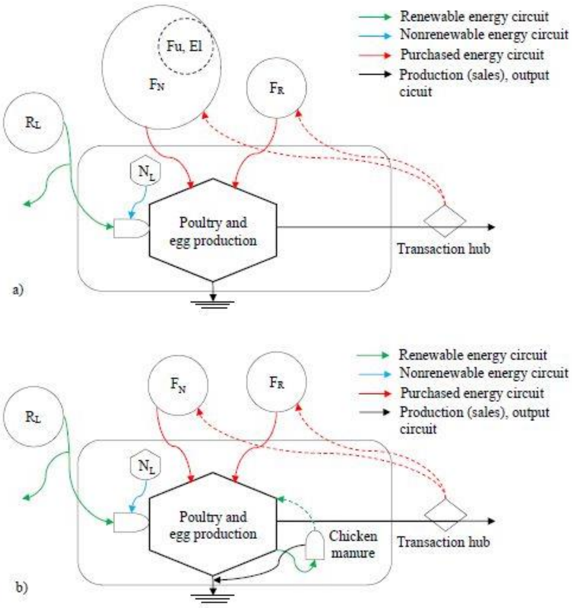


*Figure 2: Emergy flows prior to and following the shift in energy carrier use, a) Scenario A – current state, b) Scenario C – non-renewable heat and electricity withdrawal, where: RL – local renewable input; FN – purchased non-renewable input; FR – purchased renewable input; NL – local non-renewable input; Fu – purchased fuel; E - purchased electricity*

The emergy of all purchased inputs used for the production under consideration was determined by *P1* method. In addition, the emergy of sun, wind and rain was taken into account considering the free-range area for laying hens stock. These values were determined by adopting the same methodology, exergies and solar transformities as in [9,12,14] with use of local data on solar radiation, precipitation and wind conditions. Derived emergy flow is negligible in comparison to utilized emergy derived from other sources (purchased) listed in Table 7. For comparison purposes, the emergy of fuels was also derived under the assumption of the exergy of such carriers based on [26] and solar transformity on the basis of [9] for coal, and in accordance with [12]. As a result of the calculations, cumulative emergy values were determined: 9,53E+16 seJ for coal and 1,72E+17 seJ for fuel oil, respectively. Such results are very close to the ones determined on the basis of the monetary equivalent *P1*, presented in Table 7.

The total emergy of consumed electricity was determined on the basis of derived total exergy and assumed solar transformity equal to 1.6E+05 seJ [9] and it is equal to 4.97E+17 seJ. It was found to be nearly 40% lower than the value determined on the basis of the monetary equivalent P1 (6.85E+17 seJ). The emergy of human labor was determined on the basis of the methodology specified in [35] for average salaries in the agricultural sector in Poland in 2016 [36].

The emergy of the remaining components, purchased for production, was determined on the basis of the mean prices in 2016 and the monetary equivalent. Table 8 contains a summary of the relevant sustainability parameters, environmental load and effectiveness calculated for the analyzed production. These parameters were determined for the current production (Scenario A) as well as for other alternative, where fuels (Scenario B), as well as fuels and electricity, with a specific conversion coefficient (Scenario C), are substituted with energy from derived poultry manure. In scenarios B and C, in addition to the change of fuel, the change (decrease) of the emission fee is also considered.

According to the procedure applied in [37] *REN**, *ELR**, ratios were determined which do not take into account the emergy related to human labor and services. This procedure ensures that the modified parameters are not sensitive to the variations in the labor costs, which may be different in specific regions of the country. Consequently, the differences in comparable production scenarios will be less significant. Determination of the *REN** and *ELR** parameter was applied regardless of the effect resulting from the adopted level of sustainability of human labor discussed earlier in this work.

In the analyzed production, the renewability factor REN is equal to 0.5615, while ELR is 177.10, and the resulting EYR is very close to 1. The latter result is due to the fact that virtually all production components are purchased. Human labor also needs to be considered as one of the resources transmitted outside. The farm forms an employer that creates jobs locally, and the owners are employed in the administration. The company also obtains feed, straw and water from its surroundings.

The *REN** value is 0.5574 and the *ELR** is greater than the value of *ELR* and equal to 178.40. It results from the omission of human labor in the calculations, for which a large share of renewable resources was assumed. Very high values of the *ELR* and *ELR** indices result from the fact that basically all means of production come from purchase, with a low share of renewable emergy in *P1*. In the case of the cited papers, the assumptions about the renewability of human work and fodder play an important role, hence the low *ELR* values in the cited articles.

For instance, in case of the conventional poultry production on a smaller scale analyzed in [12] the following parameters were gained: *ELR* = 5.21, and *EYR* = 1.19. In this case, the low level of renewability was assumed with regard to the basic components of the feed (22% and 10%) as well as labor (only 5%). In turn, in the study [11] carried out with regard to small poultry farms (family-operated organic rearing system and orchard-based field husbandry system), the following results were calculated: *ELR* 3.10 and 3.44, as well as *EYR* 1.10 and 1.11. In this case, it was assumed (in both cases) that the renewability ratio of feed was equal to 25%, and human work was considered as renewable to a ratio of 60%. In [13], in the part concerning the rearing of ducks, the results gave the ratios equal to *ELR* = 8.85 and *EYR* = 1.01. In this case, the renewability ratio of 10% was assumed for feed and 90% for human labor. We can note the very low level of *EYR* in this production.

The variations in terms of the values of environmental factors, related to the adopted levels of energy management of the production, which is the basis for the analysis in the study, results from the ratio of fuels and electricity in the total resource use for production. The ratios of these resources in production costs is, respectively: for coal 0.53%, for heating oil: 0.96% and for electricity: 2.18%. These ratios are very similar in relation to the total emergy use in the production process.

The values of the parameters presented in Table 8 demonstrate that the use of manure as an alternative energy source both increases the renewability rate of *REN* process by 5.74% (when the procedure defined in Scenario C is adopted - in relation to A), and also leads to the decrease of the *ELR* by 5.46%. For the reasons provided in the paper, the value of the *EYR* indicator does not change. The *REN**, *ELR** and *EYR** parameters vary in a similar way. The use of low emission techniques allows for a substantial reduction of emission charges and a further reduction of *ELR* by 6.11% compared to the baseline.

*Table 7: Farm production emergy analysis*

| | Item | RF range 0-1 | Ref. for *FR* | Unit | Raw data | *TC*, USD | Solar transformity $\tau$ | Ref. for $\tau$ | $E_m$, seJ Investigated scenarios | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | A | B | C |
| 1 | Sunlight | 1 | [9,12,14] | J | 8.64E+13 | 0 | 1 | [9] | 8.64E+13 | 8.64E+13 | 8.64E+1 |
| 2 | Rain | 1 | [9,12,14] | L | 1.34E+07 | 0 | 31,200 | [34] | 2.07E+15 | 2.07E+15 | 2.07E+1 |
| 3 | Wind | 1 | [9,12,14] | J | 3.53E+10 | 0 | 2,470 | [34] | 8.73E+13 | 8.73E+13 | 8.73E+1 |
| 4 | Baby chick | 0.006 | [28] | num. | 6.02E+05 | 212,774.14 | 6.09E+12 | [30] | 1.30E+18 | 1.30E+18 | 1.30E+1 |
| 5 | Potable water | 0.006 | [28] | $m^3$ | 1.17E+04 | 14,548.43 | 6.09E+12 | [30] | 8.86E+16 | 8.86E+16 | 8.86E+1 |
| 6 | Water - cleaning and social | 0.006 | [28] | $m^3$ | 157.7 | 546.17 | 6.09E+12 | [30] | 3.33E+15 | 3.33E+15 | 3.33E+1 |
| 7 | Feed | 0.006 | [28] | kg | 6.16E+06 | 2,080,209.42 | 6.09E+12 | [30] | 1.27E+19 | 1.27E+19 | 1.27E+1 |
| 8 | Feed additives | 0.006 | [28] | kg | 1.58E+05 | 413,612.57 | 6.09E+12 | [30] | 2.52E+18 | 2.52E+18 | 2.52E+1 |
| 9 | Straw | 0.006 | [28] | kg | 1.04E+05 | 4,891.10 | 6.09E+12 | [30] | 2.98E+16 | 2.98E+16 | 2.98E+1 |
| 10a | Human labour – workers | 0.006 | [28] | pers. | 10 | 175,703.76 | 6.09E+12 | [30] | 1.07E+18 | 1.07E+18 | 1.07E+1 |
| 10b | Human labour – admin. | 0.006 | [28] | pers. | 4 | 70,281.50 | 6.09E+12 | [30] | 4.28E+17 | 4.28E+17 | 4.28E+1 |
| 10c | Human labour – owners | 0.006 | [28] | pers. | 4 | 70,281.50 | 6.09E+12 | [30] | 4.28E+17 | 4.28E+17 | 4.28E+1 |
| 11 | Heating oil | 0.006 | [12] | kg | 5.24E+04 | 31,293.41 | 1.32E+05 | [30] | 2.77E+17 | 0 | 0 |
| 12 | Coal | 0 | [13] | kg | 8.41E+04 | 17,172.25 | 6.70E+04 | [30] | 1.35E+17 | 0 | 0 |
| 13 | Electricity | 0 | [13,26] | kWh | 8.65E+05 | 71,215.31 | 2.20E+05 | [30] | 6.85E+17 | 6.85E+17 | 0 |
| 14 | Disinfectants | 0 | [28] | kg | 323 | 8,184.92 | 1.48E+13 | [30] | 4.78E+15 | 4.78E+15 | 4.78E+1 |
| 15 | Buildings and equipment | 0.006 | [28] | $m^2$ | 12,040 | 94,554.97 | 6.09E+12 | [30] | 5.76E+17 | 5.76E+17 | 5.76E+1 |
| 16a | Emission fee | 0.006 | [28] | USD | 7,556.26 | 7,556.26 | 6.09E+12 | [30] | 4.60E+16 | 0 | 0 |
| 16b | Emission fee | 0.006 | [28] | USD | 4,610.38 | 4,610.38 | 6.09E+12 | [30] | 0 | 2.81E+16 | 0 |
| 16c | Emission fee | 0.006 | [28] | USD | 4,610.38 | 4,610.38 | 6.09E+12 | [30] | 0 | 0 | 2.81E+1 |
| | | | | | | | | | 2.03E+19 | 1.98E+19 | 1.91E+1 |

*RF* - renewability factor, *TC* - total cost, $E_m$ - total emergy, $\tau$ - solar transformity, A - current production type, B - substitution of oil and coal with fuel from poultry manure, C - substitution of oil and coal and electricity generation with fuel from poultry manure

*Table 8: Farm production emergy analysis*

| Measure, parameter | Symbol | Calculation formula | Scenarios | | |
|---|---|---|---|---|---|
| | | | A | B | C |
| Extracted Energy, seJ | $E_m$ | $\Sigma E_{mRi} + \Sigma E_{mNi}$ | 2.03E+19 | 1.19E+19 | 1.19E+19 |
| Renewability, % | *REN* | $(\Sigma E_{mRi})/E_m \cdot 100$ | 0.5615 | 0.5731 | 0.5936 |
| Renewability*, % | *REN** | $(\Sigma E_{mRi})/E_m \cdot 100$ | 0.5574 | 0.5702 | 0.5929 |
| Environmental Loading Ratio, - | *ELR* | $(\Sigma E_{mNi})/ (\Sigma E_{mRi})$ | 177.10 | 173.49 | 167.46 |
| Environmental Loading Ratio*, - | *ELR** | $(\Sigma E_{mNi})/ (\Sigma E_{mRi})$ | 178.40 | 174.38 | 167.66 |
| Emergy Yield Ratio, - | *EYR* | $E_m /(\Sigma F_i)$ | 1.0001 | 1.0001 | 1.0001 |
| Emergy Yield Ratio*, - | *EYR** | $E_m /(\Sigma F_i)$ | 1.0001 | 1.0001 | 1.0001 |

A - current production type
B - substitution of oil and coal with fuel from poultry manure
C - substitution of oil and coal and electricity generation with fuel from poultry manure
$E_{mRi}$ – renewable emergy of $i$ input
$E_{mNi}$ – non-renewable emergy of $i$ input
$F_i$ – emergy of purchased goods
* excluding human labor and service

The *REN* may be 6.19% higher than the baseline. The variations in these indicators as a percentage are small. However, when we take into account the scale of production and the number of similar farms, the effects of a positive environmental impact may be significant.

## Conclusions

The conducted research and analysis lead to the following conclusions:

1. The chicken manure generated on the farm may constitute the fuel sufficient to meet the energy demand of the farm after drying. The warm air from the poultry houses provides sufficient amount of heat for the purposes of drying process. Dedicated equipment is available that enable ongoing drying of manure removed from poultry houses, without the need to store it. Combustion of the dried manure is possible e.g. in low fluidized bed boilers, or its co-combustion with other fuels in conventional solid fuel boilers.

2. The amount of energy from the dried manure is sufficient not only to replace the fuels used on the farm for heating purposes. Using a fluidized bed boiler coupled with the ORC system with the electricity generation efficiency equal to 0.18, enables generation electricity in an amount sufficient to meet the farm demand. Due to possible surpluses of the generated electricity, the proposed generation system on the farm would have to cooperate with the external power system.

3. The analysis of emergy aspects made it possible to determine the ratios of individual energy sources used in the analyzed poultry and egg production. The largest inflows of emergy area associated with feed and feed additives - 75.0% and human labor – 9.51%. Fuels and electricity together account for 5.41% of the total emergy use.

4. The basic indices of emergy efficiency and environmental renewability were determined. In the analyzed production, *REN* is 0.5615, *ELR* is 177.10 and *EYR* 1.0001. The *ELR*, which measures the environmental pressure, is very high. It is due to the fact that most means of production come from purchase, with a low share of renewable emergy. A very significant impact on the absolute value of the above indicators has the adopted degree of renewability of individual emergy resources used in production.

5. The use of chicken manure in the analyzed production as fuel allows not only to reduce the collected emergy, but also to positively change the value of individual indices. The *ELR* is reduced by 2.04% when manure is applied to substitute production fuel and by 5.44% when additionally used as fuel for electricity production. Accordingly, the *REN* increases by 2.07% and by 5.60%. Taking into account the scale of production, changes in these indicators will also result in specific economic effects. These results should also be considered taking into account the large level of egg and poultry production in Poland.

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