Energy efficiency in an integrated agro-ecosystem at the acid soil area in Mekong delta, Vietnam

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Abstract

Background: Both exergy and energy analysis methods are used for analysing energy efficiency in all kind of processes, and can be used also in agriculture. The study focuses on the connection of the three main process components (husbandry-crop-fishpond) in a typical farming household in an acid soil region in rural areas, Mekong delta, Vietnam. The concept of exergy analysis is used to underline the potential for energy efficiency in alternative processes in the agricultural system. To develop an integrated ecological system towards zero-emission, the analytical methods of material cycles and energy flows use a set of indicators of resource efficiency in a sustainable agriculture.

Results: The design of the ideal integrated farming system “Agro-Industrial Zero Emissions Systems” (AIZES) can increase the system efficiency by making use of indigenous natural materials and waste reuse, recycling. Recycling waste for energy, fish feed and fertilizing can result a decrease in half of environmental load. Using exergy analysis to calculate an indicator non-renewable yield ratio (NRYR), the systems imply sustainability of agriculture production.

Conclusions: The farming household will be able to replace fuel and electricity resulting in energy self-sufficiency to distribute surplus biogas to surrounding households. Biochar created by mixing the biomass residues with local plants can improve soil quality. Pig sludge can become nutritious fertilizer when mixed with biomass residues. Also, utilizing biogas can reduce purchased electricity.

Keywords: Agricultural system, Acid sulphate soil, Biogas, Energy efficiency, Exergy, Zero emissions

Introduction

Integrated biosystems connect all functional components in a system such as agriculture, aquaculture, waste treatment, fuel and water use [1]. Waste and by-products in these systems become inputs for an additional process step, closing the cycle of all material flows. The study of Van Huong et al. opens good perspectives for integrated biosystems like the combined orchard-fishpond-livestock system operated in Vietnam [2]. Reduction of waste implies effective decrease in energy demand in agricultural systems and thus encourages proper energy optimization approaches for evaluating systematic energy efficiency. In order to calculate with a single energy unit, an energy analysis applied to the agricultural production, focusing on the energy conversion of all materials is suggested. Reports from some European countries on energy saving measures categorize subsectors of agriculture into specific items, dividing types of energy entering the production to indirect energy (inorganic fertilizers, pesticides) and direct energy (fuels and electricity)[3]. To define energy saving potential for implementation in an agricultural production, two approaches can be considered, either applying a new type of
energy technology or improving the energy efficiency [3, 4]. Vigne et al. collected many references of diverse agricultural systems to assess the energy use [5]. The review shows that production of livestock is usually much less energy efficient than fruit or crop production. Livestock systems are reaching 1 MJ of nutrition energy per 1 MJ of non-renewable energy, while fruit, vegetables or crop can reach up to 5 or even 15 MJ per 1 MJ of non-renewable energy. Also, the study shows that energy analysis, independent of entire energy sources, is a proper way to develop energy use effectiveness.

Biogas digestion is one of the best methods for energy supply in agricultural systems since in agriculture plenty of bio-waste is generated [6]. However, there are only a few publications investigating the overall internal interactions in the integrated system of agriculture and biogas. In Germany, family farms use biogas plants as an important economic sector for rural sustainable development [7]. Biogas as a renewable energy source can be a supplement for other fossil fuels popular in rural areas [8-10]. A study of Yang and Chen [11] shows the experiences of energy analysis linking agricultural and biogas systems. The study was conducted in Gongcheng Yao Autonomous County, China, assessing energy balance through the performance of biogas engineering in a compound agricultural system. Besides, Zhang and Wang [12] carried out research on biogas at a typical household scale in a rural region in China. The main indicator used for the energy analysis is the energy return on energy investment (EROI). EROI is the ratio of the amount of energy obtained from an energy source to the amount of energy expended to produce that energy resource. [13] indicated that the EROI concept has been applied for a long time.

The comparison of energy use and energy efficiency in organic and conventional farming systems shows that organic agriculture with its sustainable production methods can be more efficient in energy utilization in e.g. livestock and ruminant production systems [14]. An evaluation of system effectiveness of biomass feedstock is represented in the paper of Wightman and Woodbury [15] and of Maier et al. [16]. By using analysis methodology of energy conversion of raw inputs to final energy services as well as assessing the energy returned on energy investment, the method provides a holistic approach to the land unit value for sustainably producing primary energy resources [15].

Exergy is of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir which usually is the environment. The cosmic exergy reflects the resource consumption which is embedded to the input flows in the ecological processes and products or services under the equilibrium conditions of environment [17]. An ecosystem analysis based on exergy accounting was conducted in a conventional semi-natural cropland in China. A comprehensive methodology of embodied cosmic exergy accounting is applied for evaluating three agro-ecosystems comprising all or a mixture of the components farmland, biogas and dairy [18]. The study points out the relationship between energy conversion and information exchange in ecological flow, as well as a suggestion of an extended exergy approach which is suitable for sustainability potential evaluation.

Exergy analysis is applied for improving the framework of exergy-based natural resource measures for sustainability of agricultural production via computation of a cumulative overall natural resource efficiency (COREA) in the agricultural context [19]. Eco-exergy, as a form of exergy, computes qualities of biomass in ecosystems. Eco-exergy of organisms or ecosystems is defined as the work energy embodied in the information. It though, has adopted a wide systematic range of ecosystems (e.g. forests) to social system (e.g. cities) excluding particular species and various economic aspects [13, 20]. Rarely has eco-exergy been applied for a comparison of biomass recycling in a system [21]. The present study is to establish a closed scheme for integrated eco-agriculture systems based on the exergy analysis and energy analysis, thereby estimating potentials for sustainable developments of ecosystems. To recover energy from waste, extended exergy accounting (EEA) is an appropriate
measure when solving the problems that stem from a monetary or a thermo-economic approach. The study offered the application of EEA to a technical alternative evaluation for recycling of non-integrated waste, integrated waste and an incineration facility [22].

The agricultural system in rural Vietnam is dispersed and performed at a small scale; thereby hardly considering resource efficiency in terms of a systematic consideration of input - output flows. Livelihoods in South-West rural regions mostly depend on agriculture. It is necessary to take the loss of resources in farming processes into account. This is related not only to economical but also to the environmental aspect because most of the farming by-products and biomass residues are not likely to be reused but largely discharged. The local conditions of the acid sulphate soil cause difficulties in the production for aqua-agro culture, because of its low pH level ranging from 4 – 5 in soil and water sheds. This results in a lack of water that is safe enough for plant irrigation on a production scale. Hence, the utilization of indigenous plants, adapted to the special conditions of acid soil, associated with the reuse of waste will be able to maximize the production efficiency. According to Taheri et al. [23] an exergy analysis incorporating both exergy efficiency and exergy destruction underlines the ineffective energy use in alternative processes. Inefficiencies in energy loss as heat and emissions occur through the irreversibility within the process to the environment. The considerable amount of energy losses not only represents extra unexpectable costs for energy purchase but also environmental side effects [24]. Indicators of comprehensive energy evaluation may include energy efficiency, exergy efficiency and exergy destruction [23]. Exergy and energy analysis methods basically are used in analysis and comparison of energy in intensive manufacturing processes. Thermodynamic methodologies manifest energy efficiency evaluation in manufacturing processes, implying exergy as well as energy balance [13, 18, 19, 21, 23, 25]. Contributions from agricultural waste need an accurate identification to calculate an unnecessary loss as well as consider potentials of waste recycle during the farming process. By the First Law of Thermodynamics, energy always is conserved in the system but can be transported over the systems boundaries [24].

Based on the energy efficiency analysis method, i.e. exergy calculation, the objective of the paper is to assess the utilization of materials derived from the system process (i.e. heat and waste) in energy forms, which is uselessly disposed of. Through estimation of energy efficiency of the present agricultural system, a closed loop scenario of the agro-ecosystem linking all components in the system is proposed., which is based on waste recycling and the utilization of the local ecosystem., Also, potential flows of input-output towards zero emission are considered for improving the agricultural system.

Methodology

Conceptual Framework

The study approach is based on the integration of resources in agriculture to create a closed ecological system, which is aimed at optimizing the efficiency of materials and energy use, i.e. maximizing the use of renewable energy resources and minimizing non-renewable resources [26]. Waste recycling through all material flows are proposed towards a zero emission system. In agriculture-based rural areas, main living activities consist of crop cultivation (or horticulture), aquaculture and livestock. The scale of household farming varies, commonly showing a combination of functional components such as crop-fishpond, animal husbandry-crop, etc... The research subject is a system of all three main components (husbandry-crop-fishpond). The design of an integrated farming system can increase the system efficiency minimizing the input of non-renewable resources. Making use of indigenous natural materials, available on the farm will minimize the cost as well as the consumption of transportation fuel. Waste recycling is considered as a production unit in the system when waste or by-products are converted into
input to within the system. By this approach, the use of non-renewable materials will be reduced enhancing system sustainability [27].

Considering integrated systems from peer literatures regarding the living conditions of the household, an agro-based industrial zero emissions systems (AIIZES) is proposed. It is an eco-agro linked system composed of functional components i.e. orchard (O) - fishpond (F) - animal shed (S) – biogas digester (D) - housing (H) - plant (P) - waste treatment (T) - ecosystem (E) as in following detailed description. This model by Le et al. was developed to achieve zero-emission in agriculture and contribute to sustainable livelihoods for farmers in the Mekong Delta [28]. It is derived from the typical model of agriculture - fishpond - livestock - biogas system.

Other components have been integrated to the system, such as a wastewater treatment system, or the natural resources available in the area as well as soil, including human activities with management functions. These components - playing a very important role in material cycles - solve environmental pollution problems from waste, in addition to creating profit for farmers. The functions of the components in the system are described as follows:

- O (Orchard) takes up products from two components S and F. Raw materials like dry leaves from trees and other plants from the local ecosystem (component E) are used for composting and biochar production (component F).
- F (fishpond) serves as nutrient storage receiving input from B, and its water can be used to irrigate the orchard (component O).
- S (animal shed) receives feeding from component O, and produces waste (manure and urine), which is the main source for components F and D.
- D (biogas digester) converts carbon and nitrogen rich waste from black water into bioenergy (CH₄). It transforms sediments from the fishpond and livestock manure from the components F and S to compost used as an organic fertilizer for component O.
- H (housing) plays the key role in controlling and managing all system activities and is directly affected by the outputs. It consumes energy converted from the biogas of D (heat and electricity). In addition, it gains benefits from the other system activities.
- P (composting - biochar plant) transforms dry leaves from component O, sludge from the biogas digester and the locally available plants from components D and E into compost and biochar to re-supply components O and T.
- T (waste treatment system) is used to treat wastewater from D and S using aquatic plants such as water spinach (Ipomoea aquatica), water hyacinth (Eichhornia crassipes) from component E and biochar (component P). After the treatment, the water from the fishpond can directly be used for irrigation of the orchard O. The biogas effluent treated by biochar filtration is reused to irrigate the crop (component O), and after completed adsorption the biochar will be recovered and re-applied in the system for component O as a source of nutrients.
- E (native ecosystem), the land with naturally growing native plants such as spinach, water hyacinth and vegetables is the place where organic matter accumulates. It serves as additional organic fertilizer for O and F to improve the soil properties. It receives compost from component P storing and metabolizing the nutrients for subsequent crops.

To develop an integrated ecological system towards zero-emission, the analytical methods of material cycles and energy flows use a set of indicators of resource efficiency in a sustainable agriculture. Analysis of energy saving must take into account input alternatives for optimum reduction of energy losses. To calculate the overall system
efficiency including the existing mass and energy balances, the exergy concept can be a quantifier for material flows in one common unit (joules of exergy) [18]. Input flows to the system are computed in form of energy flows to assess the energy efficiency through calculations of both accumulated energy and accumulated energy loss in the system. The analytical method known as “exergy analysis” focuses primarily on evaluating the resource efficiency indicators of the input and output flows in energy form. In particular, the inputs and outputs of each component in the integrated system are quantified. The overall system energy use is calculated through indicators to optimize the selection of alternatives for sustainable farming.

![Conceptual Framework for energy conservation in an integrated farming system](image)

Fig. 1 Conceptual Framework for energy conservation in an integrated farming system

Physical boundaries of the entire system must encompass a proper size for the analysis of a process [29]. The extension portion of the surrounding environment including both materials and energy, which are extracted to the system processes may be quantified. Fig. 2 shows the boundary size of the studied farming system including the combination of productive components.
Studying the boundary of the system takes the following key factors into account: biogenic flows, water flows, chemical flows, energy flows and the system sustainability [18]. It is important to also consider temporal interactions between the performance of components [30] and the chronological sequences in the system since components of agriculture vary in productive timespan.

![Fig. 2 Boundaries of the current agricultural system](image)

**Exergy analysis**

Maximizing the utilization of bio-waste from biogas, crop production, and livestock systems by recycling farming residues within the agricultural system can improve a sustainable livestock and crop production systems [11][31]. A comprehensive exergy analysis of a system has to be performed following the simple procedure shown below [32]:

- The systematic process has to be subdivided into expectably manageable system components (process or sub-process);
- The mass and energy flows of the process must be identified, and the balances must be calculated in terms of basic quantities and properties;
- A reference environment model must be chosen to obtain an acceptable analysis complexity and accuracy levels including a quantification of energy and exergy values.
- The exergy balances related to energy consumptions must be calculated.
- The energy and exergy efficiencies based on the proper measures of merits must be defined.
- Appropriate conclusions related to the evaluation of each system component are drawn and a system innovation is recommended.

The exergy concept can be a quantifier for material flows in one common unit (joules of exergy). Exergy uses thermaldinamic metrics to assess material flows extracted from the system process [17]. Due to the low quality of resources in the subsequent transformation step, exergy analysis considers both the quality and the quantity of
resources on one single scale. The ratio of yields (products) and inputs implies the exergy efficiency \( \eta \) of the process [18]. Exergy analysis (EA) considers a system or process for the balance of all inputs and outputs in unit of exergy content per time (i.e. J/yr) to evaluate the exergy efficiency (\( \eta \)) which is a fraction of the desired product to the input exergy [19].

\[
\eta \text{ (\%)} = 100 \times \frac{\text{exergy outputs (products)}}{\text{exergy inputs}} \tag{1}
\]

For the exergy efficiency of product and by-products, it implies \( \eta' \).

\[
\eta' \text{ (\%)} = 100 \times \frac{\text{exergy outputs (products and by-products)}}{\text{exergy inputs}} \tag{2}
\]

The method of analysing and evaluation input and output streams was used for the present paper. We adapted a type of network modelling method [21] of energy interaction of the whole goods and services via the statistics of total intermediate inputs and organization matrices. The energy transactions in a basic EA framework perform the flow of resources for each component of eco-agriculture system as a producer. EA uses a one-step conversion procedure to transform physical units of energy inputs of the system via conversion factors (called “energy coefficients”) into total fossil energy [5]. According to [23] the higher temperature in the system process, the smaller is exergy destruction, hence an energy efficiency evaluation would not be much different compared to the evaluation of exergy efficiency. In addition to quantifying exergy efficiency and exergy destruction, the increased process timespan leads to magnifying the exergy destruction value. Exergy efficiency plays an important role in the outcome analysis of the process. Exergy analysis accounts for energy loss and energy efficiency (\( \eta \)) from the process for a certain time (a year) due to a steady state, the exergy balance is calculated as follows [19, 33]:

\[
E_{in} = E_{out} + E_{loss} \tag{3}
\]

\[
\eta \text{ (\%)} = 100 \times \frac{E_{out}}{E_{in}} = 100 \times \frac{E_{in} - E_{loss}}{E_{in}} \tag{4}
\]

\( E_{loss} \) represents the waste or by-products exergy or the output streams represented by exergy unit divided by time that contrasts with exergy destruction due to the recovery characteristics.

For an exergy analysis, both exergy destruction (irreversible within the process, not serviceable for work and should possibly be eliminated) and the exergy losses to the environment are computed.

\[
E_{in} = E_{out} + E_{loss} + E_{des} \tag{5}
\]

\[
\psi = \frac{E_{out}}{E_{in}} = 1 - \frac{E_{loss} + E_{des}}{E_{in}} \tag{4}
\]

The performance of exergy efficiency (\( \psi \)) is better in comparison with energy efficiency (\( \eta \)) [23]. The loss refers to the amount of exergy that is destroyed, whereas the waste refers to the amount of exergy contained in matters, which actually or potentially causes pollution. Then cumulative extraction of exergy equals cumulative loss and cumulative waste. Enrico Sciubba (2001) [34] represents exergy algebra for efficiency and cost calculations that the outputs \([O]\) consist of the desired product \((O1)\), of some energy rejection to the environment \((O2)\), of a by-product \((O3)\), and of some waste \((O4)\).
The internal transfer function of a process (i.e. each component in the system) links the outputs with the inputs, is called conversion efficiency or transformity unit. This study selects a number of energy conversion coefficients (or equivalent factors) from research literature which are suitable to local conditions for the calculation of embodied exergy in agricultural systems.

In general, the efficiency of systematic farming process is analyzed in an exergetic concept referring to the sustainability of agriculture, which is defined by the set of indicators of sustainable agriculture employed in this study (Table 2) [25]. Three basic resources are natural renewable resources (RR), non-renewable resources (NR), and purchased non-renewable (PN) resources. In the extent of the study, purchased renewable resources (PR) (i.e. human labor) are not taken account. Labor can be attributed to purchased renewable (PR) resources when householder has to hire labor power [25]. It is also renewable resource (RR) in the case of the current study area. The majority of human labor (20 people) is household family members; hence, there is no cost.

### Table 1 Indicators of exergy efficiency for sustainable agriculture (adapted from [25])

| Indicators | Implication                        | Equation                                      | Positive* |
|------------|------------------------------------|-----------------------------------------------|-----------|
| RI         | Renewability Index                 | RI = (RR/(RR + NR + PN))                      | ✓         |
| ELI        | Environmental Loading of Investment| ELI = (PN/(RR + NR))                          |           |
| IYR        | Investment - yield ratio           | IYR = PN/Y                                   |           |
| ERYR       | Ecosystem resource - yield ratio   | ERYR = (RR + NR)/Y                            | ✓         |
| STv        | System transformity               | STv = (RR + NR + PN)/Y                        |           |
| NRYR       | Non - renewable yield ratio        | NRYR = (NR + PN)/Y                            |           |

*: Higher is better

### Case study description

Experiments in this study were carried out at a farm household of 8.1 ha of land use for farming in Long An Province (10°36’24″N 106°8’31″W). The local weather conditions show an average temperature of 27°C and an average annual amount of evaportranspiration of up to 2,000 mm. There are three productive components in the operation of the farm: piggyery, fish breeding, and an orchard. The farm is raising piglets for porker production at an industrial scale with 4,500 heads of pig. The total area of the sheds is 1,800 m². Jackfruit trees (*Artocarpus heterophyllus*) are planted with a density of 525 trees per ha on 2.5 ha of orchard. Feeds for pig and fish as well as fertilizer for the orchard are commercial products. For the fishpond, river water is used, but lime is scattered on 5 ha of ponds to increase the pH level to the range of 6.5 - 8 before raising fish. Similarly, water pumped from the river can be used to irrigate plants in the orchard after pH adjustment by lime. Hence, about 180 m³ water per day from the well are used for both living and breeding. Wastewater from the piggyery, including pig manure and washing water, is directly discharged into internal ditches and then discharged into field canals. The monthly electricity consumption mainly used for washing pigs, ventilating fans, pumping water, and human activities amounts to about 12,000 kWh (43,200 MJ). Two generators are used with a consumption of 6 liters of diesel/hour for 27 kW.
The entire system with all material flows embodied in a typical agricultural system in the acid soil area in Vietnam is presented in Fig. 3. All of the natural renewable resources serving for the whole production system include sunlight, wind, rain, surface water, soil. Natural non-renewable resources include the loss of topsoil, ground, and surface water which is basically employed in horticulture [35]. Many items in this system are purchased non-renewable resources. Inputs and outputs for each component according to the existing farming system are shown in Table 1. The data is divided into groups of both free purchased inputs and the yield referring to outputs. The exergy analysis in the present system is computed for a period of one year.

**Exergy analysis**

The input and output data sources based on exergetic analysis are shown in Table 2. The items are divided into 3 groups: Renewable resources, Natural Nonrenewable resources, and Purchased -nonrenewable resources. As mentioned above, Purchased -renewable resources (i.e. labor) are not included in this case. The energy loss of the whole system and the energy efficiency of each component compared to the entire system are shown in Fig. 4. Most non-renewable natural resources contribute large amounts of exergy to the system, in which the distribution rate of fish feeding accounts for over 80% of the total input sources. From the total yields of 19 million MJ in a year, pig and fish production account for about 99% of the total production with an efficiency rate of 59% and 41%, respectively. However, the energy loss from fish production is also the highest among the components. With 195 million MJ per year of exergy content of the total inputs, the energy loss from the system is significant, accounting for 90% total inputs. The losses mainly occur in fish production. However, because in the current system three components are operated separately, we consider the calculation of the exergy embodied in each component to identify the main cause of the energy loss. From piggery, about 70% of the energy is lost not taking...
into account the amount of pig waste. Likewise, the exergy content in the fishpond is mainly embodied in animal feeding; the fish processing causes a considerable amount of energy loss. About 95% of the embodied exergy is lost while fish feeding accounts for over 99% of the total inputs. Although the rate of energy loss from the orchard is negligible compared to the entire system, energy efficiency from cultivation is only 2% not taking into account biomass residues; thus causing 98% of energy loss in this process. It is possible to attribute the causes of the energy loss in the cultivation process to the topsoil loss (over 50% of the inputs), the other ones stemming from fertilizer and machinery (plow).

### Table 2 Inputs and yields for system components according to the present farming household system (in a year)

| Item                  | Unit | Equivalent factor | Reference | Pig production | Fish production | Orchard |
|-----------------------|------|-------------------|-----------|----------------|-----------------|---------|
| **Renewable resource (RR)** |      |                   |           |                |                 |         |
| Sunlight               | J    | 1.02E-05          | [11, 18, 21] | 1.17E+02       | 3.26E+03        | 1.63E+03|
| Wind                  | J    | 3.12E-02          | [18, 21]   | 7.08E+02       | 1.97E+04        | 9.83E+03|
| Evapotranspiration    | J    | 6.26E-01          | [11, 18]   | 1.11E+04       | 3.09E+05        | 1.55E+05|
| **Natural Nonrenewable resources (NR)** |      |                   |           |                |                 |         |
| Water                 | Kg   | 4.94E-03          | [18, 36]   | 4.94E+03       | 3.84E+00        |         |
| Ground water          | m³   | 2.00E+04          | [37]       | 1.34E+03       |                 |         |
| Loss of topsoil       | Kg   | 4.33E+07          | [5, 10]    |                 | 2.06E+05        |         |
| **Purchased -nonrenewable resources (PN)** |      |                   |           |                |                 |         |
| Diesel                | L    | 47.80+06          | [37]       | 1.74E+04       |                 |         |
| Concrete              | Kg   | 6.35E+12          | [12]       | 2.08E+05       |                 |         |
| Electricity           | kW   | 3.60E+06          | [18, 37]   | 5.18E+05       |                 |         |
| Weaned piglet         | Kg   | 2.09E+12          | [38]       | 1.37E+06       |                 |         |
| Pig feed              | Kg   | 5.22E+09          | [39]       | 3.32E+07       |                 |         |
| Lime (CaO)            | Kg   | 3.11E+06          | [40]       | 3.04E+03       | 7.09E+03        |         |
| Small fry             | Kg   | 7.98E+06          | [41]       | 7.98E+04       |                 |         |
| Fish feed             | Kg   | 2.38E+04          | [42]       | 1.57E+08       |                 |         |
| Fertilizer N          | Kg   | 3.28E+01          | [9, 43]    | 1.28E+05       |                 |         |
| P                     | Kg   | 7.52E+01          |           |                 |                 |         |
| K                     | Kg   | 4.56E+01          |           |                 |                 |         |
| Pesticide             | Kg   | 4.20E+02          | [18]       | 1.26E+03       |                 |         |
| Plow                  | Kg   | 1.80E+08          | [12]       | 2.47E+05       |                 |         |
| Sapling               | Kg   | 1.44E+13          | [18]       | 9.45E+02       |                 |         |
| Yield (Y)             |      |                   |           | 1.15E+07       |                 |         |
| Porker                | Kg   | 2.03E+07          | [44]       |                 |                 |         |
| Fish                  | Kg   | 7.98E+06          | [44]       | 7.98E+06       |                 |         |
| Fruit                 | Kg   | 1.89E+12          | [18]       | 2.48E+04       |                 |         |

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### Notes:

- a: Solar energy = (the average radiation of province) x (area)
  
  The average radiation of province = 17.5 MJ/(m².day) = 6,387.5 MJ/(m².yr)

- b: Global wind circulation= (0.4 J/m²/sec) x (3.15E+7 sec/year) x (area)

- c: Evapotranspiration, chemical energy = (area) x (average rainfall) x (density) x (Gibbs free energy)
  
  Average rainfall = 2 m/yr
  
  Density = 1.00E+06 g/m³
  
  Gibbs free energy = 4.94 J/g

- d: Net loss of topsoil = (soil loss) x (organic matter content) = 9.5 t/ha x 2.5 ha
  
  Soil loss = 9.5 t/(ha yr)
  
  Organic matter content = 20% = 0.2
Fig. 5 shows the energy flows for the current farm household system. Considering the exergy loss in the current system, the comparison of input and output in the exergy analysis reveals numerous disparities; most of the energy loss is due to fish production. Basically, the components of the system process operate individually, thus there is
no links between input and output flows from one component to the others. For each component, the exergy loss from pig production, fish production, and orchard is 68%, 95%, and 98% respectively; thus exergy efficiency is quite low, the highest is 32% of pig production, the exergy efficiency of the other two components is less than 5%

The exergy embodied in waste technically contributes to the increase in energy efficiency when it is considered as the by-product. The composition of agricultural wastes is mainly organic matters having great potential for recycling. Compared with the negligible energy from biomass residues (3,000 MJ/yr) the energy content in pig manure is several times higher (900,000 MJ/yr), also the energy content of the biogas released amounts to one million MJ/yr.

**Applied agricultural zero emission system for the farm**

In a zero-emission agricultural system, aquatic plants such as water hyacinth (an indigenous plant species) growing in a pond contribute to bio-treating the wastewater [45]. Water from such a pond can not only serve for irrigating orchards but can also directly supply fishponds without prior treatment [46] (while the current system has to treat the pond with lime). In addition, aquatic plants are used as compost to fertilize the garden. Similarly, waste from a pigsty (pig manure + urine) is digested in biogas plastic container, thereby biogas can be used as an energy source for producing electricity and heat [47]. The pig sludge is used as compost in combination with water hyacinth for pond water treatment and as fertilizer for the orchard. With a pH level lower than 5 in an acid sulphate-containing soil [48], resources in the system need to be fully utilized to improve both soil and water quality, while reducing costs for the farm.

**Table 3 Supplement items for a zero-emission system**

| **Item**                        | **Unit** | **Equivalent factor (J/Unit)** | **Reference** | **Total x 10^6** |
|---------------------------------|----------|--------------------------------|---------------|------------------|
| **Natural non-renewable resource (NR)** |          |                                |               |                  |
| Water                           | Kg       | 4.94E-03                       | [18, 36]      | 49.40E+00        |
| **Purchased -non-renewable resource (PN)** |          |                                |               |                  |
| Plastic                         | Kg       | 1.08E+14                       | [12]          | 1.57E+8          |
| Biogas sludge                   | Kg       | 3.72E+05                       | [14]          | 1.25E+06         |
| Biomass (crop residues)         | Kg       | 1.88E+07                       | [44]          | 9.13E+02         |
| Biogas                          | m³       | 2.20E+7                        | [37]          | 1.95E+06         |

Other components that need to be supplemented in the scenario of an agricultural zero emission system would be local plants such as spinach and/or water hyacinth, an aquatic pond, and plastic containers for biogas production. An aquatic pond can act as storage of sludge from biogas digesters. Floating plants (spinach and water hyacinth) in the pond function as a natural waste filtration system. This kind of plants, combined with pig sludge can increase the pH level of the water, which can be used for irrigating plants. Pig manure is digested in plastic biogas containers. Biogas and sludge generated during the digestion can benefit all components. Sludge is used as bio-fertilizer and fish feeding. Pig sludge is mixed with commercial fish feed with a weight ratio of 1: 1. Simultaneously, biogas can provide heat and electricity for the whole system when using biogas-based generators. The household will no longer need to buy fuel and pay for purchased electricity.

The exergy loss in both current and ideal systems is calculated to be up to 80% (figure 6); leading to low energy efficiency with 10% of the current system and about 16% of the ideal system. However, for the proposed system, the circulation of reused waste linking all components can reduce the loss of embodied exergy in pig and fish
production. Taheri et al. imply that a process with higher temperature will result in a reduction of exergy loss [12]. The process of digesting pig slurry produces heat at very high temperatures achieving high exergy efficiency. Other productive processes in the system occur under conditions of ambient temperature, i.e. orchard and pigsty. The causes of heat loss from these components need to investigated.

Fig. 7 shows the energy flows in an idealised system, compared to the current system presuming the case of constant output. Biogas is used as a substitute for electricity and diesel to illuminate the pigsty. About ten of LED light bulbs with a power consumption of 0.018 kW per bulb lighting 150 hours in the current system in each month only needs 324 kW per year (equivalent to 1,166 MJ per year). An average power of 62 kW can be used for other electrical appliances of the household. The remaining approximately 1.4 Million MJ/yr of embodied exergy of biogas can be converted into electricity, it can replace the amount of purchased electricity from the local power grid. Besides, biogas can also be stored and distributed to surrounding households.

The embodied exergy of biogas sludge is 65 times lower than that of commercial fish feeds. Thus, replacing commercial fish feed by addition of sludge the embodied exergy in the system can be considerably reduced. Farming experience showed, that sludge supplemented with fish feed at a weight ratio of 1:1 (equal to 78 millionMJ/yr in feed and 1 million MJ/yr in sludge) leads to the same fish yield as supplying only commercial feed. Energy input in the sludge / commercial feed combination amounts to only half the energy for fish feeding compared to the present system. However, empirical measures are needed for analysing and formulating the complete fish diets using locally available ingredients to optimize fish growth and health [49].

For orchard inputs, the recycle waste consists of jackfruit leaf, remains of pig sludge (crude protein content is 12.8% and 2%, respectively). It is possible to combine the waste with local plants (spinach and water hyacinth with 0.5% protein) to form biochar. This biochar contains the embodied exergy from biomass residues and sludge (900 MJ/yr and 450,000 MJ/yr, respectively), which can meet the nitrogen needs of the plants.

In the scenario of a zero emission system, waste recycling and utilisation of locally available resources will create closed material loops, in which power contribution of human resources will be negligible to the power contribution of the processes. Under the assumption of water resources (ground and surface water) seen as non-renewable natural resources, energy efficiency depends on the allocation of the natural resources [15].

In Table 4, the results of calculating exergy efficiency in a zero-emission system vs. the scenario in a current farming system are shown.

| Indicators | Current farming system | Zero emission system |
|------------|------------------------|----------------------|

Table 4: Indicators of sustainable agriculture in the current and a zero emission system
|       | RI   | 0.002 | ELI  | 125  | IYR  | 10*  | ERYR | 0.08 | 0.2* | STr  | 10*  | NRYR | 10*  |
|-------|------|-------|------|------|------|------|------|------|------|------|------|------|------|

*: Better

For abbreviations see Table 1

Fig. 7 Energy flows in an idealized agro-ecosystem. The recycle flow (dash line) is input imported to components, which has waste heat emission.

According to Hoang et al. [25] regarding the rankings for sustainability indicators, RI of this system is much lower than that in Organization for Economic Cooperation and Development (OECD) values (the lowest value is 1). In addition, ELI is four times higher compared to all OECD rankings in spite of the variety of range in indicators of these counties (varying from 1 to 29). Compared to the present system, the scenario reduces half of the environmental load. It is concluded that both systems have high investment costs. Other indicators have similar scores to the OECD benchmarks. The systems imply sustainability of agriculture production by NRYR which a good indicator of the agriculture sustainability.
Waste recycling for an integrated agro-ecosystem has positive effects, resolving the problem of waste and environmental pollution by reducing the purchases [50, 51]. Further research will be related to adjusting the input items to optimize the utilization of renewable resources from the local ecosystem. The next study step should aim at aggregating the input-output flows (containing waste and heat therein) along with locally available resources over the optimum time when linking the functions of the components within the farming system. The suggestion considers the effectiveness of recycle-waste flows in different directions to produce high-yield in all components.

**Conclusion**

Considering integrated systems based on the living conditions of the household, an agro-based industrial zero emissions system (AIZES) is proposed. To optimize the use of renewable energy resources and limit non-renewable resources, the study suggests a possible agricultural system making use of indigenous, available natural resources towards zero emission. The study employed exergy methods, since the methods allow for calculating material flows only in a single energy unit for assessing energy efficiency at a typical farming system in Vietnam. Based on the current farming system, other components are added to close all input - output flows towards agricultural zero emission system. Biogas digesters and aquatic ponds (with aquatic plants such as spinach and water hyacinth) enhance the benefits of the system’s energy efficiency. Pig sludge and biomass residues when utilized can reduce energy loss. Besides offering a supplement for fish feed, pig sludge can become nutritious fertilizer when mixed with biomass residues [52]. In addition, the farming household will be able to replace fuel and electricity resulting in energy self-sufficiency to distribute surplus biogas to surrounding households. Using all OECD indicators for sustainable agriculture through energy measures, the proposed zero-emission agricultural system reduces not only the loss of energy but cuts the environmental load in half and thus decreases the pressure on the environment considerably.

**Abbreviations**

AIZES: Agro-Industrial Zero Emissions Systems; COREA: Cumulative overall natural resource efficiency; EA: Exergy analysis; EEA: Extended exergy accounting; EROI: Energy return on energy investment; ELI: Environmental Loading of Investment; ERYR: Ecosystem resource - yield ratio; IYR: Investment - yield ratio; NR: Non-renewable resources; NRYR: Non - renewable yield ratio; OECD: Organization for Economic Cooperation and Development; PN: Purchased non-renewable; PR: Purchased renewable resources; RI: Renewability Index; RR: natural renewable resources; STr: System transfromity

**Authors’ contributions**

NTTT initiated the research idea and developed the system under supervision of LTH and TVT, and they also designed and organized the whole research of this study. NTTT and SLT had a lead role in the literature review and the setup of system. TVT and a group of coworkers at IER were the site engineers who brought the system into application in a household farm at Long An province, Mekong Delta area, VN. NTPT was responsible for the communication with the other partner during the site survey and data acquisition. HS, SB and GB contributed in the research idea development, especially about the energy efficiency and zero emission application for the system, and they also checked English. All authors read and approved the final manuscript.

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Competing interests.

The authors declare that they have no competing interests

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