Sustainability of biogas production: using of Shelford’s law

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Abstract. The article is devoted to proposing a method of regulation of biogas installations dissemination using Shelford’s law. It is based on the hypothesis that there is some optimal amount, and on both sides around it, the sustainability of the process will decrease because of biogas production that can affect ecosystems both positively and negatively. It declared that in different countries Shelford’s law graph could be different due to differences in both natural and social conditions. It shows that nowadays some unsustainable experience is taking place (In the case of Germany, it is using useful recourses which have to be grown and in the case of Ukraine, these are low-efficiency technologies which can be harmful to the environment). It proposes approaches to provide more sustainable biogas production using modern technologies and strategic planning.

1. Introduction
Sustainable development declared in a huge number of strategic documents. It declares the development of sociality in a way to provide quality of life and environment not worse than nowadays. One of the urgent parts of it is the production of energy using alternative energy sources. The driving force behind the development and use of bioenergy is the Renewable Energy Directive (Directive 2009/28/EC) [1] adopted in April 2009 by the Council and the Parliament of the European Union. The aim of this act is, by 2020, for 20% of the EU’s total energy consumption to be from renewable sources and for 10% of the energy used for transport be from renewable sources. A global strategy insisting on safety and sustainable aspects established in the Agenda ”Energy 2020 - A Strategy for Competitive, Sustainable and Secure Energy” [2]. The main aspects of this Agenda are set high requirements for the development of safe technologies in an appropriate and effective regulatory context. In the context (2009/C 66 E/05) [3], the European Parliament underlines the importance of biogas as a renewable energy resource. The main document which underlines the importance of sustainable energy consumption in Ukraine is “Ukraine 2020”. The main task of this document is to ensure energy security and transition to energy-efficient and energy-saving use and consumption of energy resources by using innovative technologies. According to the policy context, it highly prioritizes renewable energies, in ordinary those that could be produced locally and in a distributed manner, such as biogas. At the same time, the shift to renewable energy has to be safe, sustainable and secure. However, alternative
energetics is not always defined by sustainability as it has not only a positive effect but also a negative one.

Therefore, it is necessary to consider these factors during the design and implementation of alternative sources. Usage of best-known approaches have proposed previously, but even they cannot provide sustainability without strategic planning and regulation. So, this article is related to proposed approaches to provide an implementation of different technologies (on the example of anaerobic digestion technologies) of implementation in conditions, which guarantee sustainability. It’s worth to mention that the idea of sustainable biogas production has already been proposed by N. Bachmann [4]. However, it has not proposed to use strategical planning and its management to provide sustainability.

2. Technologies of sustainable biogas production

Anaerobic digestion researches are developing widely. Many world-known institutions work on this topic, that means that there are a wide variety of technologies developing today. Also, the amount of anaerobic digestion researches characterized by the tendency to growth (up to 14 000; figure 1). As you can see from figure 1 the number of researches in anaerobic digestion topic increased significantly from more than 100 in 1970 to more than 14,000 in 2018. The leading countries producing biogas equipment are Germany, China, USA, India, Japan, Great Britain and France. Among the world’s leading manufacturers of biogas plants are GE Jenbacher (Germany), EnerGNedalo (Netherlands), Clarke Energy (Great Britain), Dalkia (France), Deutz (Germany), Caterpillar (USA), Guascor (Spain), Baxter Engineering (Australia), Hochreiter (Germany), Eneria (France), Zorg Biogas (Germany), Firm Green Energy (USA), Biotec (Belgium), and others.

Figure 1. Dynamics of documents related to biogas production to per year (a) and its worldwide spread (b).

Sustainable biogas production technologies are that technologies, which can provide biogas production from waste (not from useful products), and characterized by high performance of destruction, with obtaining of high quality of biogas and biofertilizer, being maximally environment-friendly. It this case both utilizing waste and obtaining useful products will be provided. However, waste can be more complicated for destruction. For example, some of previous studies have devoted to digestion of chicken manure which is characterized by a high content of ammonia which can inhibit the process [5,6] and it is necessary to provide detailed biogas researches to solve this problem. Shift to the right side can be obtained by solving some issues of biogas production, such as more effective mixing [7–9], separated stages of the process [10,11], an increase of the efficiency by addition of enzymes [12] or degradation of sewage sludge [13,14]. Usage of some results of modelling will increase the efficiency of the process by
determination of optimal parameters of the process. There have been successful attempts to provide modelling of wastewater treatment [15], modelling of two-stage anaerobic digestion [11], modelling of waste co-fermentation [16, 17] and anaerobic digestion during the sorption of ammonia [18]. It also seems perspective to combine biogas production with modern chemistry nanotechnologies to provide final purification [19–22] which proves great results of organic matter destruction and is characterized by high environment safely effect. Implementation of high-efficiency technologies is important, but it will lead to sustainability only in case of environmental management based on detailed research of the current state of biogas plants development [23,24] and strategies of developments generally [25].

3. The problem of sustainability of renewable and alternative energetic

All types of alternative renewable energy sources have some disadvantages. Solar, wind and wave energy resources defined by cycles of energy production, but, for consumption, those production cycles provide the problem of excess and deficit of energy at different times. Therefore, the issue of energy storage is relevant nowadays, that is why chemical technologies such as batteries or hydrogen production have been using. Moreover, potentially, it may cause disastrous changes in ecology in case of battery life output and placing it in landfills. It is certainly possible to provide recycling of the used batteries, but it will lead to additional expenses. In some classifications, nuclear energy and hydroelectricity have mentioned as sources of alternative energetics. There are some risks of explosion during the usage of atomic energy, which must need to consider during the design and implementation of nuclear reactors. Hydroelectric power plants have defined by changing internal hydro systems of ecosystems. This effect may cause natural disasters that are not common for the ecosystems and human-populated areas. However, those facts are well-known and have considered before the construction process. Anaerobic digestion of organic matter with biogas production is more complicated and curious in terms of sustainability. The process has defined by huge variabilities of parameters. Even its implementation can be related to different aims (for example, waste recycling, biogas production, fertilizers production or its combination) which will affect the sustainability of the technology. Shelford’s law could be involved to define the state of sustainability of the number of renewable energy sources, considering their disadvantages. It is necessary to upgrade it by presenting the suitability of the human development on the oY axis and amount of the energy provided by alternative sources on the oX axis (see figure 2.

![Figure 2. Shelford’s law for the assessment for alternative energy (AE) development.](image)

It is worth noting that the graph will change with the development of new sustainable technologies of alternative energetics. For example, solving the problems with energy production
by solar or wind plants will shift to the right side of the graph. The same situation will be related to other AE fields. For example, optimization [26] and intensification [18, 27] of the anaerobic treatment will lead to an increase in biogas yield and in turn to an increase of economic attractiveness. The example of changing of Shelford’s law graph after designing of new technologies have presented in figure 3.

Figure 3. The example of changing of Shelford’s law graph after designing of new technologies.

As shown on the graph, we suppose that all parameters of the sustainability interpreted in the graph will change (character of the graph, peaks, zone of the optimum) after designing new technologies. It indicates, that one of the main principles of the EU – using the best-known practices, is very important to provide a sustainable future for Europe and the whole world. For each country, the graph will be different based on the individual country characteristics. All factors of sustainability (economic, social and ecological) will affect the graph character, peaks, and optimum zone. For example, in countries with developed economies, the salary of the people and energy costs will be higher, compared to countries with developing economics that affects the attractiveness of alternative technologies implementation. Otherwise, it is necessary to provide the development of energetic infrastructure for countries with developing economies. Also, in equatorial countries, summary of solar radiation will be much higher than in countries with a moderate climate. Social aspects such as population density will affect sustainability too. For example, it will be not sustainable if, in countries with high population density (for example India), residential buildings will be demolishing in favour of solar energy stations that need significant areas for implementation. Maybe there are some more urgent social problems such as lack of water for food. Therefore, for example, it is possible to interpret Shelford’s law graph to estimate the sustainable level of solar station implementation for some equatorial and temperate climate zones, both economically developed (figure 3).

Therefore, humanity generally and each country must find that the optimum level of implementation of alternative source and provide strategical planning according to this level and further regulation by economic instruments.

4. Shelford’s law as tool to provide sustainability

Shelford’s law of tolerance, was proposed by American zoologist Victor Ernest Shelford in 1911, that states that the presence and success of an organism depends on the degree of compliance with a set of conditions. The absence or failure of an organism can be controlled by a qualitative or quantitative deficiency or excess, or by any of several factors that may approach the tolerance limit for that organism. Each individual or population is a subject to environmental changes that create a minimum and maximum capacity to cope with any complex environmental factors. The
range in which it occurs from minimum to maximum means the limit of the body’s tolerance, and if all known factors are actually within a specific range of certain organisms, but it still fails, it is important to consider additional factors in the relationship with other organisms. Livestock Application: In agriculture, using Shelford’s Law, the animal feeding rate is calculated. This law is applied in a protected area, considering not only the optimal feeding rates but also the conditions that should be in protected areas. In microbiology, the optimal composition of the nutrient medium for microorganisms calculated, as well as the conditions of the cultivated area by this law. In zoology and ecology as a whole: Law used to predict zones where this or that creature will migrate, as well as to predict and calculate the area of residence.

5. Economics as the main instrument of regulation of the technology’s implementation quantity

Similar to sustainability, it is possible to interpret Shelford’s law to predict the level of development of alternative sources (including biogas production). In this case, it is possible to present a graph with oX axis that can predict the level of alternative sources of energy dissemination and oY axis presenting economical alternativeness. The real-life business process will provide an implementation of energy generation from alternative sources in the amount, which will be most economically attractive. In this case, it is possible to provide regulation of dissemination of alternative sources of energy using changes in economic attractiveness. For example, it is possible to ensure a green tariff for biogas, and it will provide a shift of the graph to the right. Therefore, it is possible to analyse the graph and find probabilities of dissemination of provided energy by alternative sources (%; low and high). Using Shelford’s law with economic instruments as a control method of dissemination of the technologies is presented in figure 4. The efficiency of the proposed method has proved by finding a correlation between energy costs and dissemination of biogas plants in Ukraine and the EU. According to the Report from the Commission to the European Parliament, the European Economic and Social Committee and the Committee of the Regions on European Commission [28] and Report of European Biogas Association (on the Biomethane Biogas Report) [29], the number of biogas plants in the countries with higher electricity costs (where it is more attractive to produce it) is also higher. However, it is just one of the examples, and it is necessary to prove this hypothesis additionally.

Figure 4. Interpretation of Shelford’s law graph to estimate the sustainable level of solar station implementation for some temperate (a) and equatorial (b) climate zones, both economically developed.
Figure 5. Using Shelford’s law with economic instruments as a control method of dissemination of the technologies.

In such terms, those types of graphs (figure 4 and figure 1, figure 2, figure 3) are similar, and it is possible to use them to provide sustainable development. Therefore, representing both sustainability and probability of dissemination of provided energy by alternative sources in one graph will show consistency with an existing strategy to sustainable development. Examples of sustainable (a) and unsustainable (b) development programs have presented in figure 5.

Figure 6. Examples of sustainable (a) and unsustainable (b) development programs.

Therefore, it can be interpreted as the probability of technology dissimilation (P)

\[ P = f(\sum F_p - \sum F_n) \]  

(1)

Where:
- \( P \) is the probability of technology dissimilation
- \( F_p \) positive factors
- \( F_n \); as subtraction - negative factors

It seems relevant to interpret Shelford’s law for sustainability as a mathematic formula. It is possible to use equation type:

\[ y = -x^2 + c, \]  

(2)

where:
- \( c \) will be equal to 100 (% of sustainability; it’s always 100 in the sustainability units, but it will be variable in actual dissemination unit, for example, per cent of biogas installation
dissemination; according to figure 3). In this case, “y” will be used as prognoses level of biogas plants dissemination, and “x” will be used as:

$$\sum F_p - \sum F_n$$

which interpreted as

$$x_p^2 - x_n^2$$

In this case, $x_p^2$ and $x_n^2$ are real factors, which affect biogas technology dissemination positively and negatively, respectively, and can process with simple mathematical operations (addition, subtraction). Therefore, the general view of the proposed function will be the following:

$$y = -(x_p^2 - x_n^2) + 100$$

Where

$x_p^2$ – quadratic representation of $\sum F_p$;

$x_n^2$ – quadratic representation of $\sum F_n$;

100 – represents 100% of replacing traditional energy with alternative (in the case when nothing hinders development). Proposed formula (a) and its comparison with typical Shelford’s law interpreting have presented in figure 6.

Figure 7. General view of the proposed function (a) and its comparison with typical Shelford’s law interpreting (b).

Of course, the proposed equation is not perfect, has some disadvantages, and it will be more relevant to use a polynomial equation, but it will be worse to provide manipulation with dissemination. Therefore, it is possible to affect both XP and XN by providing an implementation of legislation, and in case they are balanced and equal to zero, it will be possible to obtain maximum sustainability. In this way, the equitation has presented in the following form:

$$y = -(\sum F_p - \sum F_n) + 100 = 0 + 100 = 100$$

6. Factors that affect the sustainability of biogas production

Today, biogas production is a very variable and complex technology in terms of economics. It defined with: needs of energy (for heating and mixing), water consumption, waste purchasing (in some cases), that vary a lot in different countries and therefore may or may not stimulate
the provision of biogas technologies, operating costs, capital costs, including development of technical documentation (significantly depends on the level of salaries in the country) and a profitable component. Equally important is the state of the legislative framework related to biogas technologies implementation, including strategic documents. It means that governance politics in the field can stimulate the spread of anaerobic digestion of organic waste by providing some programs including regulation of the cost of both raw materials and products, as well as provision of economically attractive programs of financing anaerobic digestion technologies in implementation programs. Nowadays, one of the problems of sustainable biogas production is the usage of biofertilizers produced by anaerobic installations. Biofertilizer, defined by higher efficiency compared to other types of fertilizers (including compost and mineral fertilizers) as well as by higher profit compared to biogas produced during anaerobic digestion, cannot be realized. It means, that this is a useful substance that isn’t used nowadays either in Ukraine or worldwide and even provides negative changes for the environment. It is going on because of the lack of full-scale field experiments on the usage of this fertilizer. However, in scientific publications, the high potential of increasing of growing productivity of different agrarian cultures is shown. However, this is not enough to convince agrarians to use it. This fertilizer is stored in lagoons and pollutes air (by emissions), grounds (by itself) and waters (by dissemination in groundwater). The dissemination effect may be very significant as it is necessary to provide waste dilution up to 10 times which leads to an increase in the amount of produced biogas effluent (biofertilizer). The Law of Ukraine on Waste prohibits biogas plant construction without effluent utilizing. However, in the practice of Ukraine, this law is not considered, and biogas settings constructed without systems of effluent utilizing and have stored in lagoons.

7. Experience of unsustainable biogas production

As shown previously, there is a dependency between the number of biogas plants and the price of energy. It means that it seems perspective to analyse the state and sustainability of the branch in Germany, where both cost of energy (140 €/MW) [28] and the number of biogas plants (more than 11 000) [29] are the highest. Nowadays, this amount will be increased, in both EU member states and Ukraine. Generally, in Germany, anaerobic digestion technologies usage is widely developed. However, the main substrate is not waste, but plants that need to be grown [30]. It means that the full cycle of technology provides plants growth in the fields and their further use for the production of biogas. The fields that can be used to grow food, are used to produce biogas; it can also lead to degradation of the fields. In economic terms, it foresees an increase in operational costs. Therefore, this is not the most sustainable approach of biogas production, but it has provided due to the high cost of energy, which means high economic attractiveness. Biogas production from waste (generated by the food industry) can be more perspective. However, some technologies, even in this case, can be non-sustainable. For example, in Ukraine, where gas prices are significantly lower than in Germany, this approach is more common than the growing of plants (there are no notes about this technology in the industrial scale) and enterprises use anaerobic digestion not only for biogas production but also for waste utilizing. However, those technologies sometimes are still not effective in the environmental. There are few biogas installations, which provide dilution of waste up to 10 times and its storage (for example Oriellider, Dnipro), badly affecting the environment. Therefore, today it is necessary to provide anaerobic treatment of organic waste (not plants) with high economic and ecological efficiency to provide sustainability. However, now modern technologies are implemented not quickly, and nowadays there are not a wide variety of examples of industrial installations working on hard, disposing of anaerobic digestion substrates, which are characterized by high ecological and economic effect.
8. Conclusions
The use of Shelford’s law to provide an assessment of project sustainability is proposed. The proposed approach considers a lot of factors, including ecological, economic and social. Economics as an instrument to provide regulation of dissemination of technologies to provide sustainability, and the experience of both sustainable and unsustainable biogas production is described. We have described the problem of sustainability of renewable and alternative energy and assessed potential ways of risks decreasing. The practical aspects of using the proposed model of Shelford’s law to reach sustainability of alternative energy sources dissemination are shown in examples of effect on Shelford’s law graph providing of new technologies and effect of nature factors on the graph. Also, it is proposed to use economics to reach sustainability related to alternative energy source usage. To provide it, it is proposed to change the factors that affect the economic attractiveness of providing such technologies by private enterprises and then the amount that will be the most probably implemented will correspond to sustain optimum. The cases of both, effective usage of economics and ineffective ones are shown and described. The basic formula that can be used to provide a practical approach of Shelford’s law usage related to alternative energy dissemination is described, but it is required to be optimized in further works. To prove the relevance of usage of the proposed model, the factors that affect sustainability and causes of instability of biogas production are described.

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