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Husk Energy Supply Systems for Sunflower Oil Mills

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Received: 4 December 2019; Accepted: 9 January 2020; Published: 11 January 2020

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Abstract: Together with solar, wind, and hydro renewable energy sources (RES), biomass constitutes an integral part of the high-renewables electricity systems. Considerable feedstocks for electricity generation are process-based residues. Ukraine is the world leader in sunflower seed production, therefore, husk (a by-product of oil production) is a promising biofuel for combustion- based power plants. The plants consume primarily electricity and fossil fuels (natural gas or fuel oil) for steam production. Their usage affects the edible oil production cost and impacts on climate change. The above facts force us to look for alternatives. By-product (husk) utilization can reduce exhaustible energy consumption (fossil fuels and grid electricity) and mitigate climate change. The aim of the study is to make an energy and ecological assessment of biomass energy supply systems. Specifically, the electricity and heat consumption of Ukrainian sunflower oil mills is investigated. Different options of cogeneration systems are analyzed. The preferable mode of combustion-based husk combined heat and power plants is to meet their own heat demand and to sell surplus electricity. Relative gross income and carbon dioxide emission reductions are calculated. Our results show that husk utilization can meet electricity and heat requirements of edible plants. The surplus electricity may be sold to the grid. Husk combined heat and power plants may result in reduction of carbon dioxide by 200–300% and an increase of total income by 24.7–65.7% (compared to conventional energy supply systems).

Keywords: renewable energy sources; husk; energy supply; biomass; efficiency; carbon dioxide; emissions

1. Introduction

Energy plays a key role in the development of a modern civilization. Fossil fuel prices, their exhaustibility, and environmental issues have become primary challenges for mankind. This is a reason why renewable energy, including bioenergy has become a priority for most countries, including the European Union (EU) [1–3]. This fact has compelled the EU to put forward the following objectives [4,5]:

- Strengthening of energy security (decreasing imports of primary energy);
- The reduction of greenhouse gas (GHG) emissions.

To reach the above objectives, a set of measures has been identified. They include the development of renewable energy [6,7]. Recently, the targets of the Renewable Energy Directive (2009/28/EC) were updated. The new targets increase the share of renewable energy consumption (up to 27%) and cut in GHG emissions (up to 40% compared to the emissions in 1990) [8,9].

The utilization of field-based and process-based residues can contribute to providing sustainability of the energy sector [10–12]. Therefore, the biomass residue utilization meets the emerging concept of circular economy. It may be a solution related to waste management [13]. The usage of organic waste as biofuel for power generation or cogeneration is vital for development. It fits into the concept of circular economy that is a new alternative model of transforming residues into energy. This concept promotes to sustainable development [14–16].

Edible oil production is an energy intensive industry. A considerable share of energy demand of technology (electricity and heat) is met by fossil fuels and electricity from the grid. Meanwhile, these mills produce by-products. For example, for sunflower oil production it is husk. Husk could be an alternative to conventional fuels. Biofuel has a number of advantages. First of all, it is a renewable energy source. Secondly, a biomass resource management leads to significant greenhouse gas emission savings. The plant captures carbon dioxide out of the air [17]. Thus, there is a closed cycle of carbon dioxide emission and absorption. Moreover, biomass does not contain sulphur. Therefore, biomass power plants do not emit sulphur dioxide into the atmosphere. As can be seen, process-based residues can be an alternative energy source [18].

The sunflower is widely cultivated around the world. Seventy percent of all sunflower seeds are harvested by European countries [19]. Ukraine, the Russian Federation, and Argentina are the top producers of sunflower seeds [20]. Sunflower husk is a by-product of oil production. Its high energy content (around 15.4 MJ/kg) makes it possible to be used as fuel. Due to the fact that husk is carbon neutral, its utilization for energy production could mitigate climate change. However, a large share of sunflower husk is sent to landfills and its energy usage is scarce [21].

This paper examines the energy supply systems of sunflower oil mills. As a basic case, actual technological parameters of Ukrainian sunflower oil mill were considered.

2. Literature Review

Ukraine has a highly developed agricultural industry, especially edible oil production. From 2013 its share of the world in sunflower seed production ranges from 24.8% to 30.16% [22]. Sunflower seed production is stimulated by high demand for vegetable oil and its high price. Over the last five years, Ukrainian farmers have produced more than 10 million tons of sunflower seed (Figure 1). Despite the increase in production, it has been slowing down since 2012, its value is rather high, and Ukraine is ranked first among the world producers.

Both feedstock and energy costs are important factors that affect the production cost of sunflower oil. The sunflower oil industry in Ukraine is energy intensive. Electricity consumption ranges from 96.6 to 198 kWh per ton of oil and heat consumption (steam) ranges from 348 to 1184 kWh per ton of oil [23]. It is higher compared to other edible oil production [24–26]. It impacts on production cost. To raise the competitiveness of the industry, reducing energy costs is paramount.

It can be reached by means of biomass utilisation. Sunflower oil mills produce a by-product (husk). Husk and products (oil and cake) can be used to generate electricity and/or heat. This substitutes the energy resources sold (fossil fuels and electricity) and reduces greenhouse gas emission. Moreover, biomass CHPs could improve the stability and reliability of the electrical grid. In Ukraine there are about 70 husk boilers in operation. However, only three sunflower oil mills use husk-based combined heat and power plants (CHP) [27,28].

Renewable energy is of great importance in terms of preventing climate change and reducing harmful emissions [29]. The European Union (EU) supports the increase of renewable energy production [30–32]. A lot of scientists have analyzed the influence of renewable energy usage on economic indicators and economic growth [33–37].

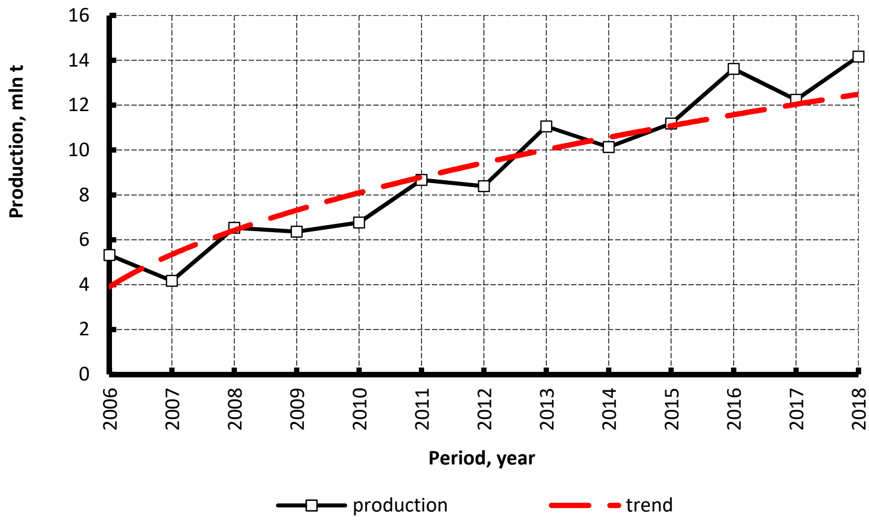

Figure 1. Sunflower seed production history [28].

Previous research has studied the energy supply systems of edible oil plants based on biomass [25,38–40]. They considered a general concept of husk application for energy supply [41,42] and the energy balance of oil mill [40]. However, this problem for sunflower oil mills has been studied insufficiently. Therefore, optimal energy supply schemes are currently being sought. The purpose of the paper is to assess the optimal mode of biomass-based energy supply systems. More specifically, the article aims to reveal specific energy consumption for edible oil production, assess the husk utilization impact on carbon dioxide emission, to analyze different options for biomass utilization.

3. Materials and Methods

The methodology used is as follows. Information and data are collected from the public domain and interactions are made with industrial's officials. Prices of energy, fuels, and products are widespread indicators. Information resources (publications, statistics, and websites) were used. The information was used for further calculations.

All kind of fuels (renewable and fossil) can be compared within the following domains: Energy, environmental, engine efficiency, economics including efficiency of technological equipment.

The energy indicators are as follows: Lower heating value and energy density. The lower heating values were taken from handbooks. The energy density is the amount of energy per unit volume (liter, cubic meter, etc.)

$$DE = LHV \cdot \rho, \ \mathrm{MJ/m^3}, \quad (1)$$

where LHV is the lower heating value of the fuel, MJ/kg; ρ is the density of fuel, kg/m^3.

The higher the energy density of fuel, the better the fuel is for consumers.

The ecological indicators may be divided into two groups: Hazardous emissions and carbon dioxide emission. Carbon dioxide emissions are discussed further. This kind of emission has two components: From fuel combustion and in due to electrical consumption. The combustion of hydrocarbon fuels results in the production of carbon dioxide, which is known as a greenhouse gas. This specific value from fossil fuel substitution can be calculated as

$$ERh = HH \cdot \eta_b^{-1} \cdot EF, \ \mathrm{t_{CO2}}, \quad (2)$$

where HH is the heat energy of fossil fuel substituted, GJ; EF is the carbon dioxide emission factor for conventional fuel, $\mathrm{t_{CO_2}}$/GJ; η_b is the thermal efficiency of the conventional fuel boiler.

The husk is a carbon dioxide neutral fuel. Its utilization reduces carbon dioxide emission compared to a certain fossil fuel. This specific value on one ton of husk can be calculated as

$$ERs = LHV_h \cdot \eta_h \cdot \eta_b^{-1} \cdot EFm, \mathrm{kg_{CO2}/t}, \tag{3}$$

where LHV_h is the lower heating value of one ton of husk, GJ/t; EFm is the carbon dioxide emission factor for conventional fuel, $\mathrm{kg_{CO2}}$/GJ; η_h is the thermal efficiency of the husk boiler (gasifier).

Emission reduction from onsite electricity production

$$ER_e = EC \cdot EFc,\ \mathrm{t_{CO2}}, \tag{4}$$

where EC is the electricity onsite consumption from grid substituted, MWh; EFc is the emission factor for grid electricity, $\mathrm{t_{CO_2}}$/MWh.

Engine performance indicators can be divided into three groups: Break thermal efficiency or engine efficiency, brake specific fuel consumption, and brake specific energy consumption.

4. Results

4.1. Sunflower Oil Mill Energy Consumption

Top 10 of Ukrainian sunflower oil mills has capacity from 500 to 970 thousand tons of seed per year [43]. Annually they process 7 million tons or 50% of sunflower seed harvest. They use electricity from the grid and thermal energy produced by burning fuel in a boiler (Figure 2). Their specific energy consumption depends on the capacity (Figure 3). Average specific energy consumption is, kWt per ton of oil: Electricity—132.5; heat—779.1.

To reduce energy consumption costs, native mills use husk as a fuel. The output of sunflower seed husk ranges from 15.94% to 18.88% or from 159.4 to 188.8 kg per ton of seeds [44]. To meet their own requirements in heat, powerful Ukrainian vegetable oil mills consume around 46–48% of husk produced (direct burning in boilers). A few mills have their own combined heat and power (CHP) plants. For example, Kirovogradoliya LLC has a husk-based CHP. The CHP was developed to meet all own energy (electricity and heat) requirements. Its electric capacity is 1.7 $\mathrm{MW_e}$ (electric efficiency—around 5%), thermal capacity is 26.7 $\mathrm{MW_t}$. This plant annually consumes up to 42.8 thousand tons of husk (around 57.8% of husk produced). It allows the mill to cover its own energy demands in heat and partially in electricity.

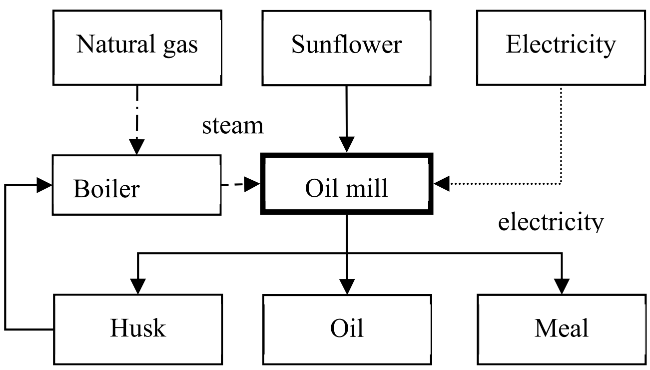

Figure 2. Basic scheme of a Sunflower Seed Oil Mill.

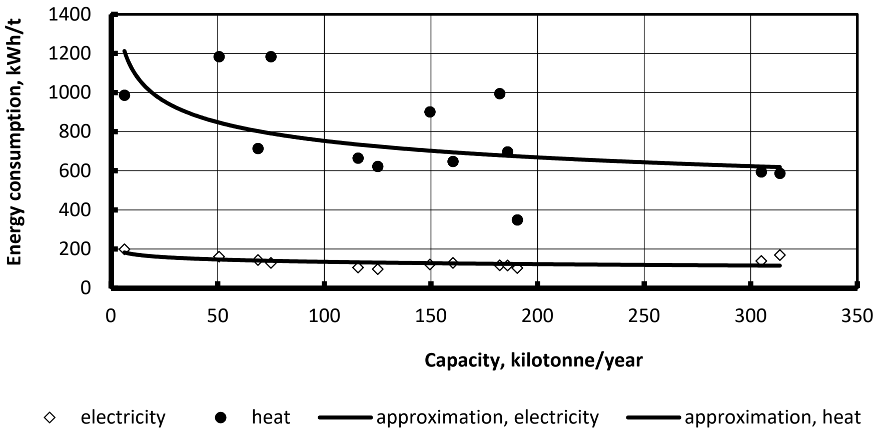

Figure 3. Specific energy consumption (kWh per ton of sunflower oil) vs. annual sunflower oil capacity (thousand tons of seed) [23].

Specific heat to electric consumption ratio of Ukrainian edible oil mills is decreasing with the increase in a plant capacity (Figure 4). The average ratio is 5.97. This means that the thermal efficiency of a CHP unit must be greater than the electrical efficiency by the same value. Surplus electricity can be sold into the grid. It contributes to its stability and to lower carbon dioxide emissions.

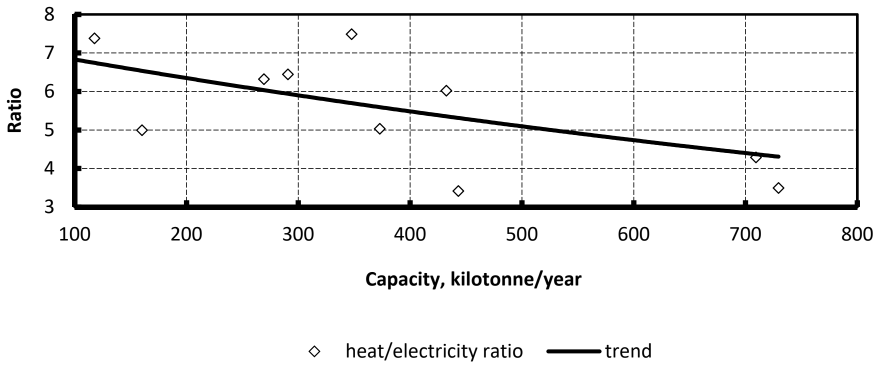

Figure 4. Heat/electricity consumption ratio vs. sunflower oil refinery capacity.

To generate electricity steam turbines and internal combustion engines running on syngas are used. Several oil mills (Galati Sunflower oil factory, Pology oil extraction plant PJSC, Centre Soya Ltd.) have experienced the gasification technology. Last mill has a gasification-based husk CHP plant (rated electric power—700 kW; heat—800 kW) (Flex Technologies Limited, London, UK) [40,45,46].

4.2. Biomass as Fuel

The main results, which are planned to achieve by biomass utilization, can be divided into two groups: Economic and environmental. All products (oil and cake [47]) and by-product (husk) may be used as fuels. Their utilization has distinctive energy and economic efficiency. They can be used in their original form or improved before utilization (gasification, liquefaction, or methanation). Husk can be burnt directly or converted into syngas, biogas, or ethanol [48]. Sunflower meat (cake) can be used as solid fuel or converted into biogas [49]. Table 1 compares parameters of selected fuels.

Table 1. Properties of selected fuels.

Parameter	Unit	Husk	Meal	Oil	Natural Gas	Fuel Oil
LHV	MJ/kg	15.4	28	37	49.75	40.5
Ash content	%	2.1	1,2	-	-	0.05
Carbon content	%	44	64	78	76	88
Bulk density	kg/m^3	95–170	>600	920	0.72	940
Energy density	MJ/m^3	1463–2618	>16,800	34,040	35.82	38,070

Their improvement can get better both environmental and economic indicators of oil production. They can be used in steam boilers to substitute conventional fuel (in Ukraine it is natural gas). If products and by-product substitute natural gas (for steam generation), husk utilization has the best economic result (difference between cost of natural gas substituted and market price of any products and by-product) (Figure 5). The above calculations have been made for one kg. The above differences per one kg of biofuels are, UAH/kg: Husk—4.88; meal—3.32; oil—(−8.22). The sunflower oil is more expensive than natural gas. Therefore, husk as a fuel has an advantage. Husk energy potential is enough to cover energy demand in electricity and heat (Figure 6). It is estimated that the potential electricity production is four-fold higher than the electricity demand. In addition, the heat requirement is a third of the husk potential thermal power production. Excess power and heat can be delivered to external consumers.

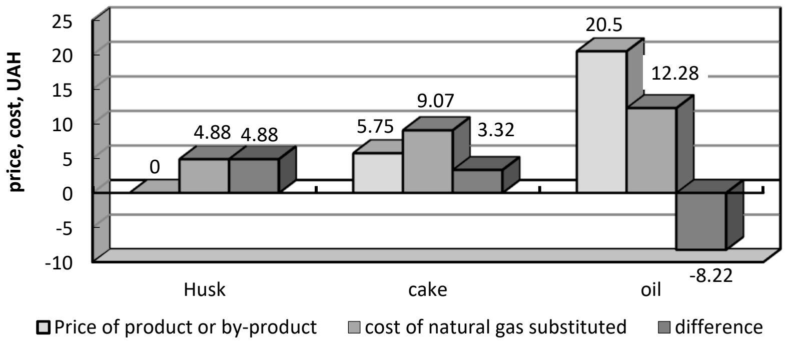

Figure 5. Market prices and cost of natural gas substituted.

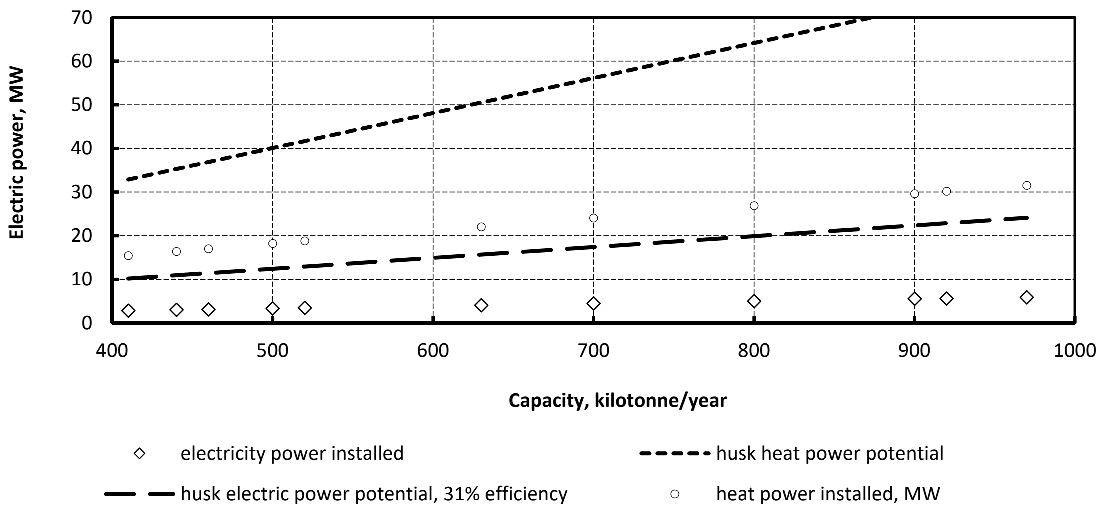

Figure 6. Installed and potential electric power vs. sunflower oil refinery capacity.

4.3. Carbon Dioxide Emission

Ecological indicators may be divided into two groups: Hazardous emissions and carbon dioxide emission. In the study, carbon dioxide emissions were discussed further. This emission consists of two components: Fossil fuel combustion and in due to electricity consumption. For Ukrainian sunflower seed oil mills the first component ranges from 48 to 96 kg per ton of seed processed. The second component ranges from 37 to 77 kg per ton of seed processed.

According to our calculation, one ton of husk (used for steam production) reduces carbon dioxide emission and this range is from 790.10 to 1162.53 kg (Table 2). It corresponds to 51.3–75.5 kg of carbon dioxide per one GJ of thermal energy.

Table 2. Ecological impact of husk utilization.

Conventional Fuel	Volume of Fossil Fuel Substituted by One ton of Husk, t(m^3)	Carbon Dioxide Emission Factor, kg_{CO2}/GJ	Carbon Dioxide Emission Reduced, kg per ton of Husk
Natural gas	428.44	56.10	807.60
Fuel oil	0.38	79.00	1162.53

Electricity consumption for a technological process is the largest sources of emissions for sunflower seed oil mills. Emissions from electricity consumption by any mill are calculated by applying an "emission factor" to the quantity of electricity consumed. Emission factor for grid electricity is taken from an official source. For Ukraine, carbon dioxide emission factor per kWh of electricity consumed is equal to 0.709 [49] or 0.896 $kgCO_2/kWh$ [50].

According to our calculations, power generation from husk (condensate steam turbine, electric efficiency of 31%) reduces carbon dioxide emission by 0.707 kg per kWhe (or 938 kg per ton of husk). Additionally, cogeneration has the potential of 1305 kg per ton of husk. Its carbon dioxide emission reduction potential depends on electrical efficiency (Figure 7). The last factor is prevailing. Gasification-based husk CHP plants allow higher value of carbon dioxide emission reduction compared to combustion-based husk CHP plants.

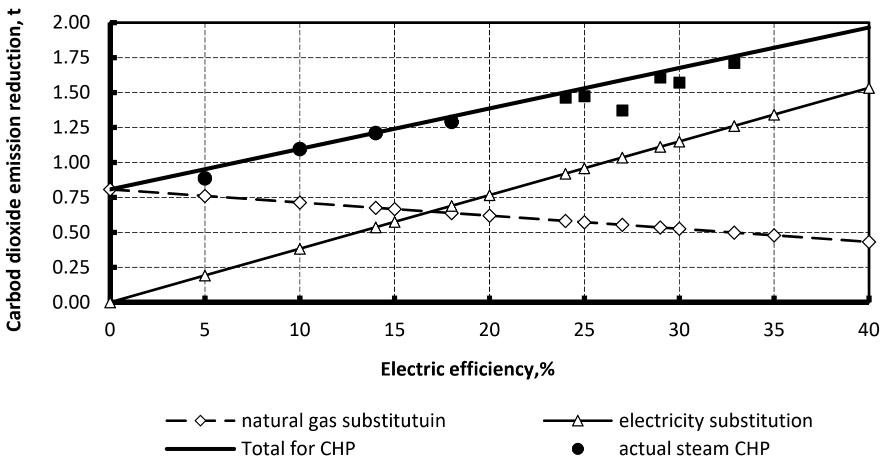

Figure 7. Carbon dioxide emission reduction potential per one ton of husk.

4.4. Energy Supply System Based on Biomass

There are three possible husk utilization pathways: Heat production only, electricity generation only, and combined power and heat generation.

Sunflower husk contains ash (at average 2.1%) [51]. The composition of this by-product of combustion includes calcium, potassium, micro elements, etc. Therefore, the ash can be used as a component to produce fertilizer [52]. Moreover, it is suitable as a filler for the production of ceramics [53]. Its price is more than EUR80/t. Therefore, ash sale can give additional income.

Sunflower husk can be used to generate electricity and heat production. The first pathway substitutes electricity bought, the second—fossil fuels (natural gas, fuel oil, coal, etc.) bought. Their ratio is

$$RCs = \eta_e \cdot \eta_b \cdot Epr \cdot LHV_{ng} \cdot 3,6^{-1} \cdot \eta_h^{-1} \cdot NGpr^{-1},$$

where LHV_g is the lower heating value of natural gas, MJ/m^3; E_{pr} is the price of electricity, UAH/kWh; NG_{pv} is the price of natural gas, UAH/m^3; η_e is the electric efficiency.

Internal combustion engines and gas turbine generators have the highest electric efficiency as compared with steam generators (Figure 8). They can be run on liquid or gaseous fuels. Therefore, husk to be used in the above method must be converted into combustible gas: Syngas or biogas [54,55]. Gasification technology is currently being used and biogas technology is under development.

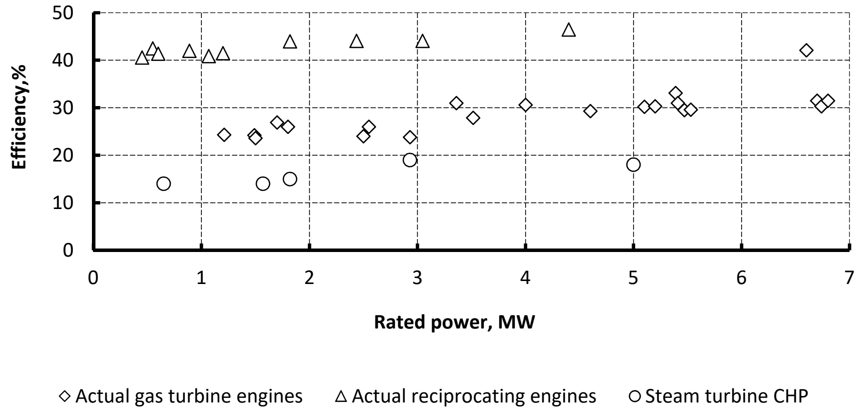

Figure 8. Electric efficiency of gas turbine engines, reciprocating engines, and steam turbine combined heat and power plant CHP (adapted from [56–65]).

Electricity generation can substitute electricity whose cost is lower than solely heat generation (substitution of natural gas). Cogeneration allows mills to reduce more costs of conventional energy bought (Figure 9). As can be seen (Figure 9), the increase in electric efficiency of CHP (and, therefore, the increase of electricity generated) results in the increase of economic benefits.

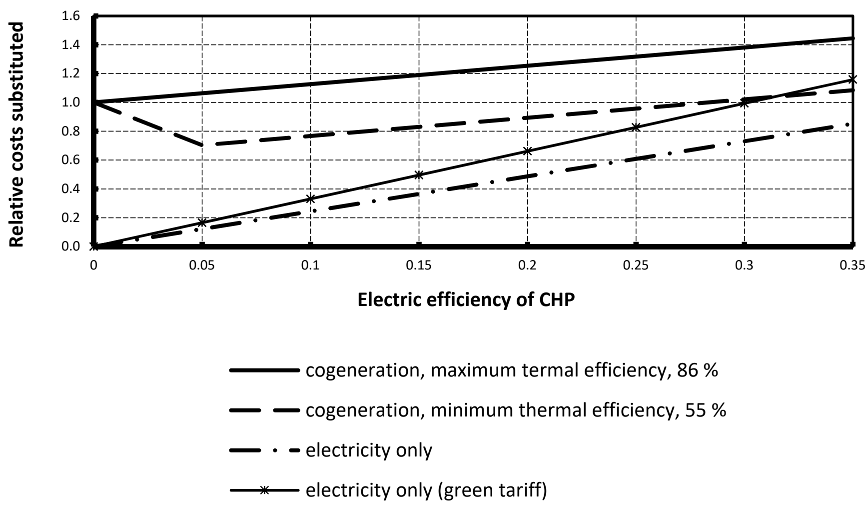

Figure 9. Economic efficiency of CHP (developed by authors).

Husk utilization's economic efficiency depends on the electric efficiency of a CHP plant and can be calculated as

$$RC = \eta_b \cdot LHV_{ng} \cdot \frac{\eta_t \cdot \eta_e \cdot \frac{Epr}{3.6} + NGpr \cdot \frac{(\eta_t - \eta_e)}{\eta_b \cdot LHV_{ng}}}{\eta_h \cdot NGpr},$$

where η_t is the total thermal efficiency of CHP; LHV_h is the lower heating value of husk, MJ/kg.

The more conventional energy resources are substituted, the higher income is made. The possible energy supply technologies are as follows (Figure 10): 1—steam turbine combined heat and power generation plant (CHP) via husk combustion; 2—gas turbine (GT) CHP via syngas combustion; 3—internal combustion engine (ICE) CHP via syngas combustion; 4—gas turbine or internal combustion engine with organic Rankin cycle (ORC).

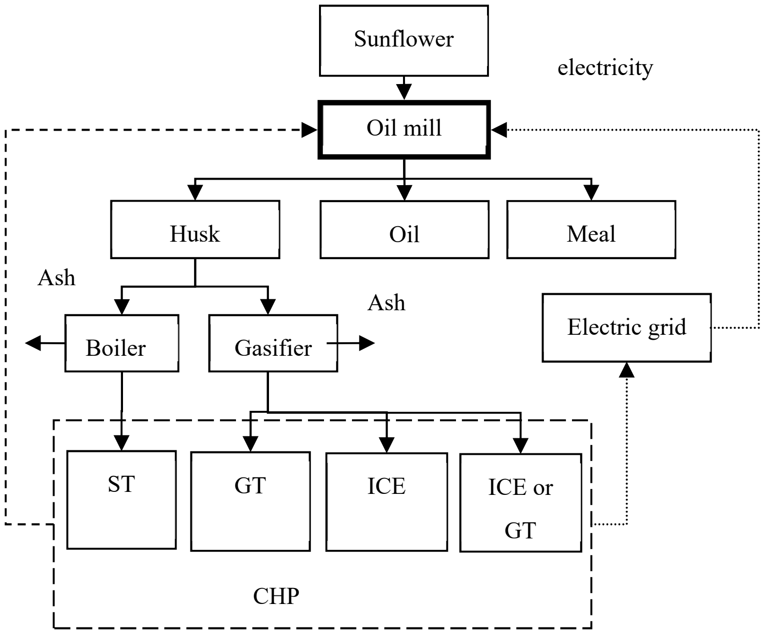

Figure 10. Energy supply technologies of Sunflower Seed Oil Mill (developed by author).

4.5. Principles of Energy Production

Ukrainian sunflower oil refineries use husk for steam production. Only some plants have CHP, but they cover only part of the electricity required.

There are three pathways of energy production by CHP (Table 3). The first pathway is to meet its own electricity requirement. However, in this case CHP cannot cover its own demand in heat. To correct the situation an additional steam boiler must be used. The second pathway is to meet its own heat requirement. In this case a CHP plant generates surplus electricity. It may be sold by green tariffs to electricity grid. For both cases, the remaining husk can be converted into pellets. The third pathway is the following. The husk combustion-based CHP plant can cover requirements in both electricity and heat. This energy supply system could have adapted the heat to electricity production ratio. If there is actual heat to electricity ratio (*HERa*) of a certain sunflower seed oil mill and total efficiency of a CHP plant then necessary electric efficiency (η_t) is

$$\eta_e = \eta_t \cdot (1 + HERa)^{-1}.$$

During operation of a certain mill, the heat to electricity ratio may vary. In this case, surplus electricity can be delivered to the national grid.

Table 3. Relative gross income and carbon dioxide emission reduction.

Pathway of Energy Production	Combustion-Based CHP	Gasification-Based CHP
	Gross income	
The first pathway	1.17	1.16
The second pathway	1.25–1.26	1.64–1.66
The third pathway	1.16	-
Husk for heat only	1	-
	Carbon dioxide emission reduction	
The first pathway	1.60	1.20
The second pathway	2.11–2.16	3.58–3.66
The third pathway	1.85–1.87	-
Husk for heat only	1	-

The gross income comprises three pillars: Cost of natural gas substituted, cost of electricity from grid substituted and sold to the grid by green tariff, and cost of husk pellets produced. Carbon dioxide emission reduction includes two components: Substitution of natural gas (or another conventional fuel) and electricity generation. The relative values of gross income and carbon dioxide reduction (the base is husk utilization to meet heat requirements only) are presented in Table 3. The second pathway of energy production has the best economic and ecological results. In this option, the cogeneration unit uses all available husks. Prerequisites for success are the sale of excess electricity by the green tariffs to the grid and the full use of thermal energy for oil production. Therefore, the prospect energy supply scheme is shown in Figure 11.

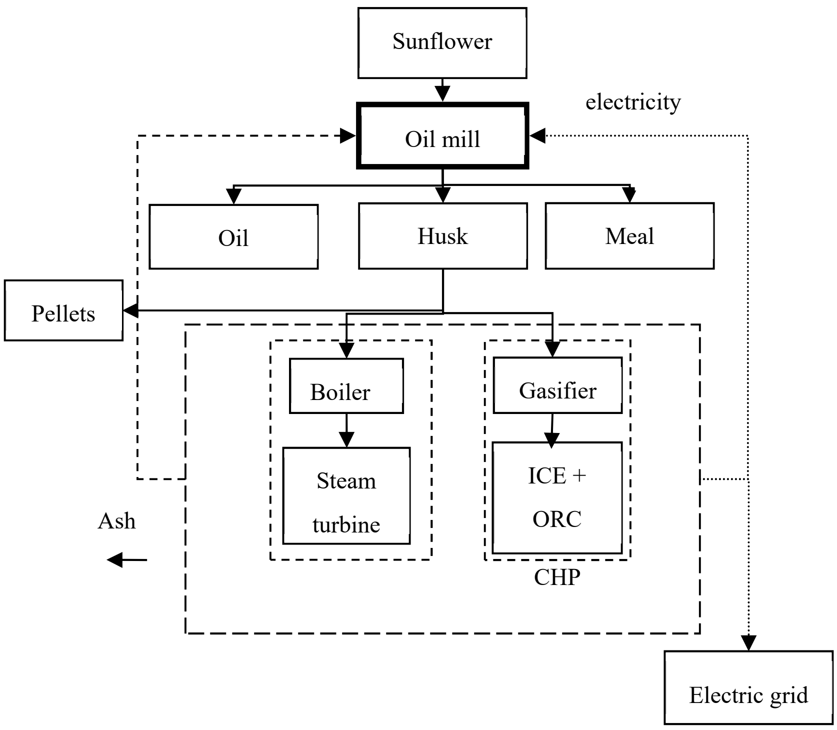

Figure 11. Energy supply scheme of Sunflower Seed Oil Mill (developed by author).

As can be seen, the best strategy for CHP development is to cover heat demand by CHP. As compared with husk utilization for heat production only, it allows mills to increase total income by 21–23% and reduce carbon dioxide emission by 70–73%. Gasification-based technologies may be profitable if their specific investment costs are not more than 40% that of combustion-based technology.

5. Conclusions

The primary goal of biomass utilization is to reduce production costs and carbon dioxide emission. The ecological benefit of husk (as biofuel) is that it is a carbon neutral source of energy. CHP plants ensure the most ecological effect.

The increase of mill capacity results in the decrease of specific energy consumption and heat/electricity consumption ratio. To reduce production costs and carbon dioxide emission, Ukrainian mills utilize sunflower seed husk (primarily to cover requirement in heat). Its consumption ranges from 46% to 57.8% of total husk production.

Heat to electricity consumed ratio of oil mills does not coincide with heat to electricity generated ratio of CHP plants. Therefore, different modes of CHP have been analyzed. The preferable mode is the design of CHP plants to cover heat demand of an oil mill. This option may increase total income by 24.7–65.7% and cut carbon dioxide emission by 201–366%. Either way, excess electricity is sent to the grid. In addition, the remaining husk may be used for pellet or green electricity production.

Energy content of husk exceeds energy demand of any edible oil plant. Husk utilization allows the plants to reduce carbon dioxide emission, kg per ton of oil produced: Heat generation—142; power generation—174; combined power and heat generation—274.

Gasification based husk CHP provides higher electricity efficiency, gross income, and carbon dioxide emission. However, this technology is not mature enough.

At further work, impact of annual operating hours and investment costs on economical indicators are expected to be studied.

Author Contributions: Formal analysis, methodology, V.H. and A.K.; Investigation, G.M., U.M., and D.G.V.; Writing—original draft, V.H. and A.K.; Writing—review and editing, V.H., A.K., G.M., U.M., and D.G.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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