


Article

# Using Biofuels for Highly Renewable Electricity Systems: A Case Study of the *Jatropha curcas*

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Received: 27 June 2019; Accepted: 30 July 2019; Published: 6 August 2019



**Abstract:** Recent movements for the decarbonization of the electricity sector have become a priority for many countries around the world and will inevitably lead to the sharp decline of fossil-fuel-based energy. Energy from fossil fuels is to be replaced by renewable energy sources (RES), although the transition will neither be cheap nor smooth. One sustainable and environmentally friendly alternative to fossil fuels and which will take a considerable share in the increasing supply of renewable energy resources is biofuels. There are various types of biofuels used in practice; however, biodiesels represent one of the most popular and widespread ones. This paper focuses as a case study on the byproducts of *Jatropha curcas*, a crop and a plant that is already used for biofuel production and which is subsequently employed in electricity generation in *Jatropha curcas* producing regions. This paper identifies the limitations and prospects of *Jatropha curcas* utilization. Also, *Jatropha curcas* is compared to other materials suitable for biomass generation. An economic analysis for a 2 MW biofuel powerplant was conducted incorporating various market-related risks. The study shows that at current prices, net profitability can be achieved using *Jatropha curcas* byproducts for producing electricity.

**Keywords:** renewable energy; biofuels; electricity generation; power sector; biomass; *Jatropha curcas*

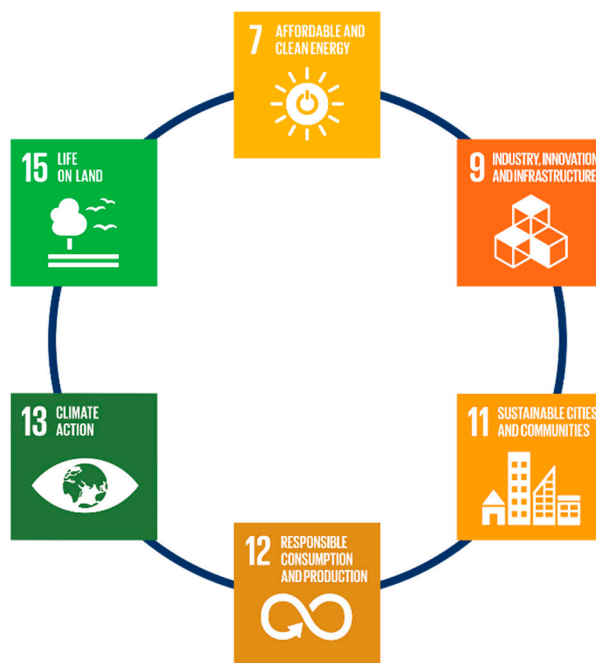
## 1. Introduction

On 1 January 2016, the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda—adopted by world leaders in September 2015 at an historic United Nations (UN) summit—officially came into force. Over the next fifteen years, with these new Goals that universally apply to all, countries mobilized efforts to end all forms of poverty, fight inequalities, and tackle climate change, while ensuring that no one is left behind [1].

Electrification of rural areas in developing countries is considered fundamental for reducing energy poverty and meeting the SDGs. Provision of electricity to rural areas through national grids is costly per unit of electricity because rural consumers are more scattered and typically buy less electricity per consumer compared to urban consumers. Rural households are assumed to consume at least 250 kWh per year and urban households 500 kWh per year.

Instead of bringing the national grid to rural consumers, community scale electricity production units may be a more realistic solution for supplying electricity at a reasonable cost per kWh, and biomass-based electricity generation is deemed to have potential [2,3].

The SDGs build on strategies that create economic growth and addresses a range of social needs including education, health, social protection, and job opportunities, while tackling climate change and environmental protection [1]. This paper analyzed the use of biofuels in systems and aimed mainly on six goals of the SDGs, depicted in Figure 1. These goals are interconnected to each other, because one supports the rest.



**Figure 1.** Contribution of this article to Sustainable Development Goals [1]. Source: Own results based on Reference [1].

Mitigating global climate change requires decarbonizing the electricity sector as it is a major source of global greenhouse gas (GHG) emissions. With roughly half GHG emissions coming from coal-fired power plants, electricity from natural gas presents another alternative—a lower carbon technology. The optimal strategy for picking ideal technology will depend on the ultimate costs of each technology as well as the social costs from GHG emissions. These analyses are increasingly discussed in many countries around the world [4]. Based on The National Climate Assessment, in just the US, due to the change in climate, hundreds of billions of dollars are lost, mainly because of heat-related deaths, coastal property losses, and lost wages in outdoor industries due to the presence of heat waves [5,6]. Transition to lower carbon emission technologies will neither be cheap nor smooth; however, the status quo is still fairly expensive, even though the cost is not directly visible.

The introduction of alternative fuels is a logical step, which is continuously being done around the world. The first generation of alternative fuels introduced in large numbers comprised oilseed, sugarcane, and other oil containing food and animal feed crops. First generation bioethanol is mainly produced from sugar containing plants or cereal (grain) crops. Vegetable oils are also used after a range of conversion to fatty acid methyl or ethyl esters. Even though, second, third, and fourth generation are currently under research both by commercial and scientific circles, first generation is still the main representative of alternative fuels [7].

This paper focused on the use of *Jatropha curcas* as a potentially useful source of renewable energy, which was discussed in October 2008 in the European Parliament. The proposal was that one-fifth of energy should come from non-food-related alternatives. Because this crop does not compete with food production, it can become a choice for assessment by international investors and biodiesel processors, energy producers and international institutions. In addition, it would be appropriate to support

oilseeds which do not compete with food crops with certain subsidy incentives for areas, particularly in developing countries, because of employment policy.

The paper is organized as follows: Section 2 provides a short literature review. Section 3 focuses on the materials and methods used in our study. Section 4 presents the results and discussions. Finally, Section 5 concludes by summarizing the main findings and implications.

## 2. Literature Review

The genus *Jatropha curcas*, belonging to the family Euphorbiaceae, contains 322 genera and 8910 species ranging from large woody trees to simple weeds. The site of origin is tropical Central America, from where they spread to many tropical and subtropical areas, including India, Africa, and North America. The plants are monoecious and contain yellow to red latex. The lists are alternate, simple or palpatad. The flowers are single-sex, the fruit is fleshy [8].

The most significant of the species is *Jatropha curcas* (hereto referred to as *Jatropha curcas*), which is widely grown in the tropics. It is a monoecious shrub or low tree, which grows up to 5 m. Its smooth shiny bark, which can appear greenish brown or yellow, has a paper-like look and tends to easily peel. The watery pink latex can be pulled out mechanically and, after use, the color turns brown. The branches are ascending, coarse, and glabrous [8].

In addition to the production of biofuels, oil from the fruits of this plant is used, including in the production of candles, soaps, hair conditioners, and lamp oils. *Jatropha curcas gossypifolia* and *Jatropha curcas multifida* also have the same area of origin. The seeds of these two species contain oil which can be used in a similar way. *Jatropha curcas multifida* is also popular as an ornamental and decorative plant, similar to *Jatropha curcas podarica* [9,10].

Of course, as a plant spread in the tropical and subtropical regions of most continents, *Jatropha curcas* has several distinct local names in each of these regions.

*Jatropha curcas* has high ecological adaptability. As a succulent plant that excretes water through its leaves during the dry season and also because it is deeply rooted, it is very well adapted to grow in semi-arid conditions. With increasing humidity, plant production also increases. Despite the fact that this plant survives the average annual rainfall of 250–300 mm very well, it needs an average annual rainfall of at least 600 mm to produce flowers and then fruit. Optimal precipitation for seed production is 1000–1500 mm. Higher precipitation can then cause fungal and fungal attack on the root system [11–16].

*Jatropha curcas* can withstand extremely high temperatures very well, which, however, affects yield, while even a small frost can permanently damage the plant. Enzymatic-catalytic chemical reactions of plants that affect biomass production are controlled by van't Hoff effect (increasing the temperature by 10 °C leads to an increase in the rate of reaction two to three times). The optimum temperature for its growth ranges from 20 °C to 28 °C. It can be grown at low altitudes. *Jatropha curcas* is not sensitive to daytime. It is very suitable for growing in areas of high light intensity, but it is not suitable for growing in shady places. Flower formation is not dependent on latitude, and the plant can bloom at any time of year.

The properties of the oil, especially its quality and density, are important for biodiesel production. Physical properties include density, viscosity, and low temperature properties. Density is important in relation to the calorific value of the fuel. Viscosity characterizes the degree of fluidity and, with a high viscosity, the fuel system is more stressed, or can cause that the fuel could not be pumped. Low temperature properties are important to ensure operation in winter. Of the chemical parameters, the acidity number in relation to the corrosive environment and especially the presence of unsaturated fatty acids is important. Multiple bonds in fatty acids are more susceptible to oxidation processes.

The physical and chemical properties of *Jatropha curcas* are quite variable. Characteristic properties are greatly influenced by the environment and genetic interaction, such as size, weight, and oilseed. The quality of the oil, especially the content of fatty acids, is further influenced by the maturity of the fruits during harvesting, the method of processing and storage. In general, it is necessary to ensure

low oil contamination, low acid value, low phosphorus, water, and ash particles and to increase its oxidation stability. The crude oil is relatively viscous. It is characterized by low fatty acid content, which improves storage conditions. When stored, a higher content of linoleic acid may pose a problem, which may cause the oil to be more susceptible to oxidation. The high cetane number guarantees a low flash point. The oil contains a small amount of sulfur, resulting in lower SO<sub>2</sub> emissions during combustion [17–21].

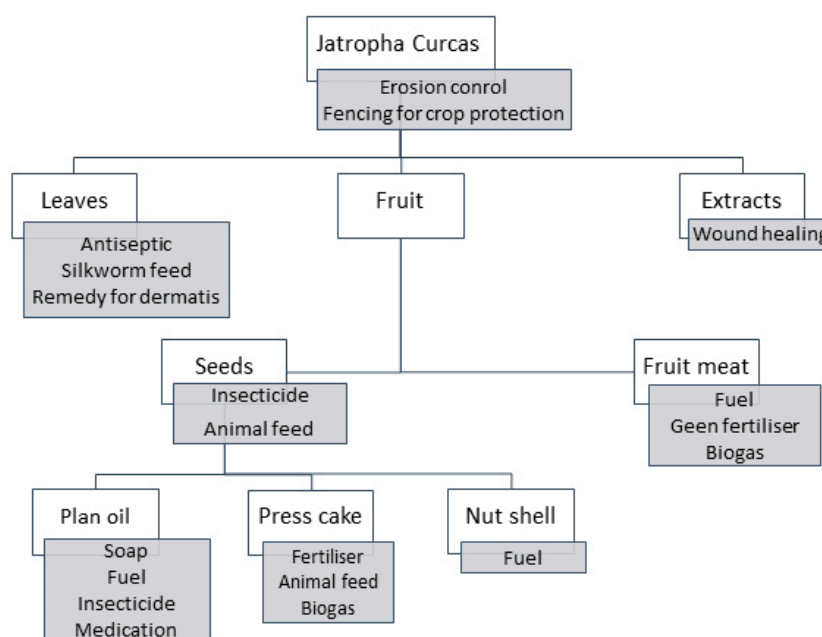
It is possible to obtain an oil yield higher than 1500 kg per hectare of this plant. Yield starts from 18 months, but an economic yield is obtained from the third year after planting. Based on experimental field conditions, the average seed yield with existing varieties under irrigation conditions after 3 years is estimated to be 4 to 5 tons per hectare (4 to 6 kg/plant/year). However, farmers also recorded a yield of 6 tons of seed per hectare. The most limiting factor of *Jatropha curcas* besides water is the relatively high laboriousness. Therefore, large-scale *Jatropha curcas* plantations are not economically feasible today (under the current conditions) and it can be replaced only partially by mechanization. Three common planting densities can be identified: 1111, 1666 and 2500 trees per hectare equal to a squared spacing of 3.0 by 3.0, 2.4 by 2.4, and 2.0 by 2.0 meters per tree [22].

*Jatropha curcas* oil is adequate to be used as a raw material in biodiesel production which meets American and European standards [23,24]. Additionally, the press cake can be used as a fertilizer and the organic waste products can be digested to produce biogas (CH<sub>4</sub>). Average oil content of dry seed on a mass basis is 34% [25]. Full composition is shown in Table 1.

**Table 1.** Proximate and ultimate analysis, and higher heating values of the raw materials [21].

| Sample                           | Moisture (%) | Proximate Composition (% Weight, Dry Basis) |              |       | Ultimate Composition (% Weight, Dry Basis) |      |      |      |      |
|----------------------------------|--------------|---|--------------|-------|--|------|------|------|------|
|                                  |              | Volatile matter                             | Fixed Carbon | Ash   | C  | H    | N    | S    | O    |
| <i>Jatropha curcas</i> seed cake | 4.08         | 73.7  | 19.06        | 7.24  | 52.12                                      | 6.91 | 5.01 | 0.7  | 28   |
| Seed cake biochar                | 9.28         | 40.02                                       | 46.62        | 13.36 | 61.31                                      | 3.55 | 3.77 | 0.38 | 17.6 |
| <i>Jatropha curcas</i> Shell     | 10.57        | 71.52                                       | 17.64        | 10.84 | 40.8                                       | 5.9  | 1.53 | 0.43 | 40.5 |

*Jatropha curcas* is a promising plant for both bio-energy supply and socio-economic development in developing countries [26,27]. Full usage of *Jatropha curcas* is depicted in Figure 2.



**Figure 2.** Usage of *Jatropha curcas*. Source: Own results.

For comparison of the biogas yield from *Jatropha curcas* cake with other raw materials which are used frequently for commercial biogas production see Table 2, which shows some examples of agricultural, industrial, and municipal residues as well as energy plants with properties of *Jatropha curcas*.

**Table 2.** Comparison of *Jatropha curcas* properties with other raw materials [28,29].

| Raw Material                                 | Yield [ $\text{m}^3 \cdot \text{t}^{-1}$ ] |
|--|--|
| <i>Jatropha curcas</i> cake                  | 360  |
| <i>Jatropha curcas</i> mesocarp              | 200  |
| <i>Jatropha curcas</i> cake and mesocarp mix | 310  |
| Fat (deep-fry)                               | 960  |
| Glycerin                                     | 930  |
| Wheat  | 660  |
| Rapeseed residues                            | 640  |
| Hay  | 450  |
| Straw (barley)                               | 345  |
| Molasses                                     | 340  |
| Fruit pomace                                 | 280  |
| Grass cuttings                               | 220  |
| Maize silage                                 | 200  |
| Organic municipal waste                      | 100  |
| Kitchen residues                             | 80   |
| Starch process water                         | 65   |
| Manure (poultry)                             | 62   |
| Potato mash                                  | 40   |
| Manure (cattle)                              | 22   |

Source: Own results.

The biogas yield of  $360 \text{ m}^3$  of biogas per ton of *Jatropha curcas* is much higher than comparable energy plants, castor (*Ricinus communis*) and Camelina (*Camelina sativa*) [29].

The cake is excellently degradable. The cake residue has a high heating value between 16–17 MJ/kg; however, incineration would destroy the nutrients, which are needed on the ropa plantations to grow the trees. Therefore, *Jatropha curcas* is more suitable for biogas production than burning in steam powerplant [30–34]. Since the *Jatropha curcas* cake is excellently degradable, biogas production would be currently the best alternative. *Jatropha curcas* cake has a volume of  $360 \text{ m}^3 \cdot \text{t}^{-1}$ . Mesocarp, as opposed to the cake, is not well degradable. However, mesocarp could have significant value for biogas production and increase biogas yields in a powerplant Mesocarp yield is roughly  $200 \text{ m}^3 \cdot \text{t}^{-1}$  [28]. When both *Jatropha curcas* cake and adequate amount of *Jatropha curcas* mesocarp (adequate portion from collected fresh fruit bunches) are processed into biogas, it would be approximately  $310 \text{ m}^3 \cdot \text{t}^{-1}$  [35].

A significant number of articles about *Jatropha curcas* biodiesel are focused on fuel properties [36–41], different approaches and processes used to produce biodiesel from *Jatropha curcas* [29,42,43], comparative studies on fuel properties of *Jatropha curcas* with other biodiesels [44–47] or evaluation of its impact on countries [24,48–54]. As many studies were conducted that analyzed utilization of this plant for biodiesel, no comprehensive study is known to the authors that deals with the use of *Jatropha curcas* byproducts for a biogas power plant.

*Jatropha curcas* has the great advantage of being grown on agriculturally unsuitable soils, causing it to produce low or no carbon deficiencies in these soils offering immediate and lasting benefits. It is true that the yield of these plants is higher than that of *Jatropha curcas*. On the other hand, the price of seeds can be four to five times higher than that of *Jatropha curcas*. Another disadvantage of these plants is the high demand for them in the food industry [55–57].

Biogas produced from *Jatropha curcas* can be further processed or used as is. Biogas as a mixture consisting mainly from methane and carbon dioxide can be purified in an absorption column, where the  $\text{CO}_2$  is removed. The choice of a specific gas sweetening process depends mostly on the material itself, the required selectivity, costs, environmental requirements, and the final product. Usually amine

compounds, physical solvents or hybrid (mixed-solvent systems that contain both amine and a physical solvent) are used [58]. This pure natural gas can be simply put into gas pipeline and distributed or liquified and either transported via LNG (liquid natural gas) tanker or used as high energy-density fuel for trucks or buses [59].

Another application, which will be also discussed in this paper, is burning biogas in a combustion chamber to produce steam and generate electricity by steam turbine. This application is an easier application of biogas than previous ones, because there is not any separation of gases. Detailed theoretical technology is discussed for example in Reference [60].

### 3. Materials and Methods

The process of making biofuels from *Jatropha curcas* was carried out as follows: after extraction of oil, *Jatropha curcas* cake and mesocarp were obtained. The first step of biogas production was pretreatment. Generally, all processes of this kind start with pretreatment step, where pH is regulated for optimal fermentation usually by adding acid or base. The bacteria of the individual process steps have different pH values at which they can grow optimally. The optimum pH for hydrolyzing and acid-forming bacteria is 4.5–6.3. Methane-forming bacteria need a pH in the neutral range of 6.8–7.5. If the fermentation process is in one tank—bioreactor—the pH must be properly maintained. The pH is usually adjusted spontaneously within the system via the alkaline and acidic metabolic products formed during anaerobic decomposition. Normally, the pH released by the carbon dioxide in the neutral range is balanced. If a drop in pH is observed, substrate delivery must be immediately reduced or stopped to give bacteria time to break down the acids present.

The fastest fermentation rate was observed when oil cake was incubated in 0.1 mol·L<sup>-1</sup> NaCl at 20 °C. Biogas production rate went up to 0.0015 m<sup>3</sup>/kg per day [61]. Temperature is important to monitor, because it affects all biochemical processes. As the temperature rises, the speed of all processes in the reaction increases, and another undesirable reaction may occur. Also, by changing the temperature and, hence, the speed of the processes, the dynamic equilibrium of the process is disrupted. It is, therefore, necessary to maintain a constant temperature for a stable course of anaerobic decomposition. Commonly, there are three typical temperature ranges that suit individual bacteria: psychrophilic (below 20 °C), mesophilic (25–40 °C) and thermophilic (above 45 °C).

After this pretreatment, the biogas production rate increased 5 times between the 1st and 5th days of fermentation when compared to fermentation without pretreatment. After this period, a sharp decrease in the biogas production rate was observed. The next step was fermentation. This process is usually done by species either from bacteria (*Bacillus licheniformis*, *Bacillus subtilis* or *Lactobacillus*) or microorganisms like *Filamentous fungi* [62,63]. The reactor was designed as a continuous stirred-tank reactor (CSTR), so the goal was to keep the highest production rate during the whole process. A CSTR was picked because it is easy to manage optimal temperature, it has low operational costs, and it always produces the same resulting product. On the other hand, the batch reactor had differences in product quality and the temperature could not be simply managed. Plug flow reactor (PFR) is by far the most expensive type of reactor and its strengths would not have been much used in this experiment.

A culture medium was continuously fed into the bioreactor to maintain the steady state. The bioreactor continuously leaves biogas and effluent with *Jatropha curcas* residue.

To ensure a stable and steady combustion of biogas, a compressor was put before the combustion chamber. The compressor kept the volume of biogas at a defined level so that process was safe.

A simplified process schema is depicted in Figure 2, below. After pre-treatment of the *Jatropha curcas* mix, the treated material enters the bioreactor where biogas is produced. Biogas is compressed and burnt in the combustion steam chamber to produce steam that enters a steam turbine which produces electricity.

An economic evaluation for biogas power plant fueled by the *Jatropha curcas* plant was done for a 2 MW biogas power plant. In economic evaluation, a mix of *Jatropha curcas* cake and mesocarp was



considered, which means that  $310 \text{ m}^3 \text{ t}^{-1}$  was taken as an average biogas yield. This and other main parameters for a 2 MW power plant are presented in the Table 3.

**Table 3.** Technical data for a *Jatropha curcas* power plant.

| Raw Material  | <i>Jatropha curcas</i> Cake/ <i>Jatropha curcas</i> Mezocarp |
|---|--|
| Dry substance (%)   | 35   |
| Biogas yield ( $\text{m}^3$ )                             | 310  |
| Energy yield ( $\text{kWh t}^{-1}$ )                      | 1695   |
| Available raw material ( $\text{t year}^{-1}$ )           | 26,000   |
| Operation period ( $\text{d year}^{-1}$ )                 | 365  |
| Net operation time ( $\text{hr year}^{-1}$ )              | 7884   |
| Average daily operation time ( $\text{hr.d}^{-1}$ )       | 21.6   |
| Fertilizer production ( $\text{t year}^{-1}$ )            | 18,200   |
| Annual biogas yield ( $\text{m}^3 \text{ year}^{-1}$ )    | 8,060,000  |
| Annual energy yield ( $\text{MWh year}^{-1}$ )            | 44.064   |
| Total electrical capacity (MW)                            | 2  |
| Annual electricity production ( $\text{MWh year}^{-1}$ )  | 16,366   |
| Plant electricity consumption (%)                         | 5  |
| Net electricity production (Q) ( $\text{MWh year}^{-1}$ ) | 15,519   |

Source: Own results.

Dry substance was considered 35%, which is the commonly required level. It was assumed that there would be technological breaks of 2.4 h every day in the process, so the operation period was 7884 h per annum. The analysis of the 2 MW biogas power plant determined it would produce fertilizer in a volume of approximately 18,200 tons if considering a 26,000 tons of input material and 30% decrease of volume after the biogas production process.

These technological parameters served as a basis for the economic evaluation of the proposed investment project. The profitability of the project depends on revenues and costs. Project revenues (TR) are calculated as a product of price (P) and quantity (Q).

$$TR = P \times Q \quad (1)$$

Quantity is deterministic and depends on the technological process. Price of electricity is considered to be fixed.

Costs for the biogas electric power plant consist of two parts: fixed cost (FC) and variable cost (VC).

$$TC = FC + VC \quad (2)$$

Fixed cost consists primarily of the cost for a power plant. The authors requested offers from various suppliers and calculated an average price for a power plant to be approximately \$3 million. Another type of cost important for the analysis was annual operational costs that were mostly part of the variable costs. Operation can be broken down into the following items: personnel (operation, supervision), consumables (gasoline), maintenance (electro-mechanical, biological), insurance, and administration. Depreciation was set to 20 years [64,65]. Emission allowances for  $\text{CO}_2$  were not considered in this analysis.

Another important part of the economic analysis is how much of the material input is needed. In order to fulfil needs for 2 MW a power plant, at least 26,000 tons of feedstock is needed. It is assumed that the material for biogas production is bought from a processor at 7% of the price of *Jatropha curcas* oil. *Jatropha curcas* oil is strongly correlated with palm oil price which is indexed at main commodity exchanges in Southeast Asia [43].

It is crucial to determine future movement in price of palm oil as it is a basis for *Jatropha curcas* oil price. For price prediction, ARIMA (AutoRegressive Integrated Moving Average) and Augmented Dickey Fuller test (ADF) were used [66,67].

ARIMA models are used for time-series forecasting. The aim of the ARIMA models is to describe the autocorrelations in the data. The ARIMA models, also called Box–Jenkins models, are models that may possibly include autoregressive terms (AR), moving average terms (MA), and differencing operations.

One of the most important models in econometrics is the random walk, which is basically an AR(1) process.

$$y_t = y_{t-1} + u_t \quad (3)$$

Equation (3) is the driftless random walk. If a constant is included, it becomes the random walk with drift. To determine if an AR( $p$ ) process is stationary involves examining the roots of its characteristic equation. Given the following AR( $p$ ) model, it can be said to be stationary if when written in the lag operator notation, the  $\varphi(L)^{-1}$  converge to zero:

$$y_t = y_{t-1} + u_t \quad (4)$$

$$y_t = \varphi(L)^{-1} u_t \quad (5)$$

If this is the case, the autocorrelations decline to zero as the lag length is increased. For an AR( $p$ ) process to be stationary, the roots from the characteristic equation:

$$1 - \varphi_1 z - \varphi_2 z^2 - \dots - \varphi_p z^p = 0 \quad (6)$$

all need to lie outside the unit circle, i.e., are greater than 1. The random walk is an example of a non-stationary process, as its roots lie on the unit circle not outside:

$$z = 1$$

$$y_t = y_{t-1} + u_t$$

$$y_t = L y_{t-1} + u_t \quad (7)$$

$$y_t(1 - L) = + u_t$$

$$1 - z = 0,$$

where  $(1 - z)$  is the characteristic equation and the root ( $z$ ) lies on the unit circle. The same principle applies to higher orders too:

$$z = 2$$

$$y_t = y_{t-1} - 0.25 y_{t-2} + u_t$$

$$y_t = L y_t - 0.25 L^2 y_t + u_t \quad (8)$$

$$(1 - L + 0.25 L^2) y_t = u_t$$

$$1 - L + 0.25 L^2 = 0$$

$$(1 - 0.5z)(1 - 0.5z) = 0$$

In the above example, both roots lie outside the unit circle, so the AR(2) process is stationary. The same applies for higher orders of lags too, although it becomes increasingly difficult to factorize these. Further characteristics of an AR( $p$ ) process are that the mean and variance of an AR(1) process are:

$$E(y_t) = \frac{\mu}{1 - \varphi_1}, \text{var}(y_t) = \frac{\sigma^2}{(1 - \varphi_1^2)} \quad (9)$$



The Augmented Dickey Fuller test (ADF) is test for a unit root in a time-series sample. This test is for a larger and more complicated set of time-series models and a statistic value of test is a negative number. The more negative it is, the stronger the rejection of the hypothesis that there is a unit root at some level of confidence. The null hypothesis is that the variable contains a unit root, and the alternative is that the variable was generated by a stationary process [28].

The extended regression used in the ADF test can be expressed in its most general form as:

$$\Delta Y_t = \mu + \gamma Y_{t-1} + \sum_{j=1}^p \alpha_j \Delta Y_{t-j} + \beta_t + \omega_t \quad (10)$$

where  $\mu$  is the drift term,  $t$  denotes the time trend, and  $p$  is the largest lag length used.

One of the most important economic factors that affect profitability and therefore feasibility of using *Jatropha curcas* byproducts is the price of this crop on the market. As *Jatropha curcas* is not a commodity, it is necessary to derive its price based upon other oil producing crop in this region, such as palm oil. Palm oil price evolution given by index Mundi [68] is depicted in the Figure 3.

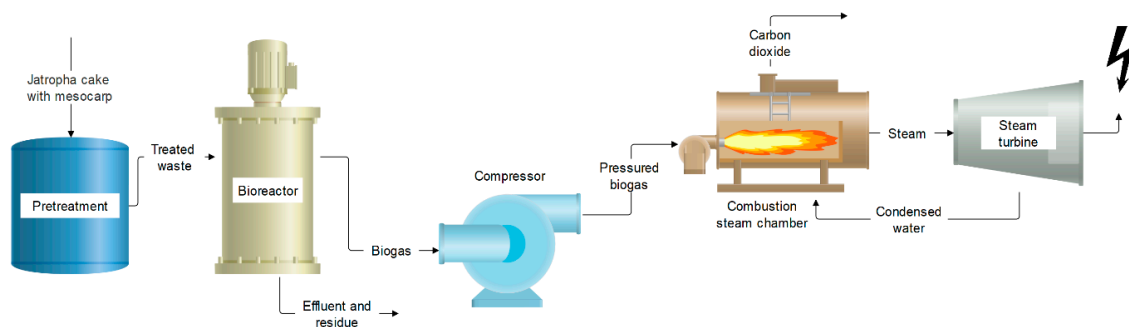


Figure 3. *Jatropha curcas* biogas power plant. Source: Own results.

Data in Figure 4 show that while in between 2006 and 2008, there has been a growing trend, in 2008 the price fell to a minimum level of approximately \$450 per ton. After 2008, prices recovered to an all-time high of approximately \$1250 in 2011. After that the price has been falling. In January 2017, the price reached a local maximum at \$825 per ton and since then, the prices are going down to a level of \$600 and below per ton.

Based on the numbers in the analysis, the following indicators of profitability are calculated: payback period, net present value, and break-even point.

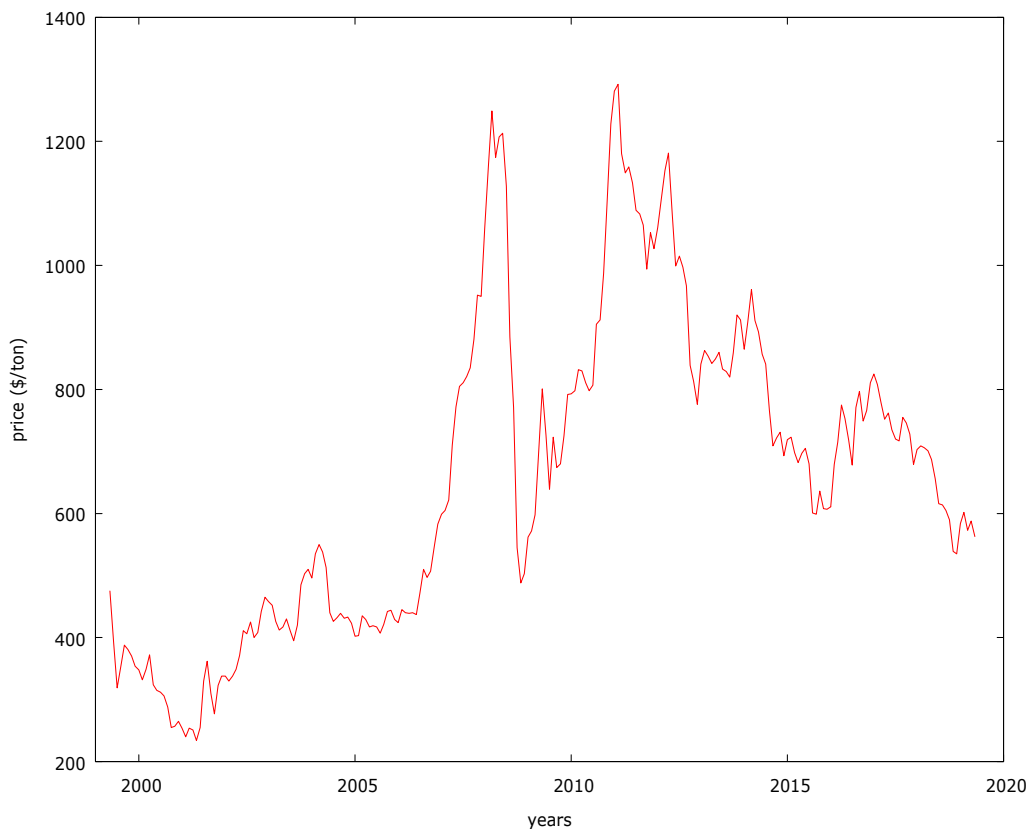
Payback period ( $PP$ ) shows how long it takes to recover the initial investment ( $C_0$ ) through annualized cash flow ( $CF$ ). It is calculated as follows.

$$PP = \frac{C_0}{CF} \quad (11)$$

Net present value is the difference between the present value of cash inflows and the present value of cash outflows. Net present value is used in capital budgeting to analyze the profitability of an investment or project, where  $r$  stands for a discount rate.

$$NPV = -C_0 + \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \dots + \frac{CF_t}{(1+r)^t} = \sum_{t=0}^n \frac{CF_t}{(1+r)^t} \quad (12)$$

Net present value is calculated for the period of  $t = 20$  years as it represents best the physical depreciation of the power plant.



**Figure 4.** Evolution of *Jatropha curcas* price since 1999. Source: Own results.

Break-even point (*BEP*) is the point at which cost and revenue are equal. It means that there is no net loss or gain, and one has “broken even”.

$$BEP = \frac{FC}{P - VC} \quad (13)$$

where *P* stands for output price (electricity), *FC* are fixed costs, *VC* are variable costs.

In order to conduct the profitability calculations, it is necessary to define the economic variables. They are given in the Table 4 below.

**Table 4.** Economic data for *Jatropha curcas* power plant.

| Items                     | Value     |
|---------------------------|-----------|
| Fixed cost (\$)           | 3 million |
| Operational cost (\$p.a.) | 152,000   |
| Input price (\$/ton)      | 39.76     |
| Output price (\$/kWh)     | 0.11      |
| Discount rate (%)         | 0.5       |

Source: Own results.

Fixed cost was simplified to only the purchasing price of the biogas powerplant. Input price was calculated as 7% fraction of the predicted *Jatropha curcas* price. Output price was given as fixed, based on the currently prevailing prices in *Jatropha curcas* producing regions. Discount rate was set to 8% on average, based on risks given for similar projects in the area [69,70]. In the calculations of NPV, the discount rate was simulated in the range of 1–16%. Cost structure is represented in Table 5 below.

**Table 5.** Cost structure for a *Jatropha curcas* power plant.

| Items  | Value |
|--|-------|
| <i>Jatropha curcas</i> cake and mesocarp (%) | 87    |
| Operational cost (%)                         | 13    |

Source: Own results.

The cost structure shows that the material costs for *Jatropha curcas* cake and mesocarp are the most important ones with nearly nine-tenth of total costs.

#### 4. Results and Discussion

In order to proceed to an estimation of an ARIMA model, it is essential to test the variable for the existence of a unit root. The most common test is the Augmented Dickey Fuller test as introduced in the methodological section. For data  $N = 232$ , it includes 2 lags of  $(1 - L)$  price (max was 12, criterion modified AIC) with unit-root null hypothesis:  $a = 1$ , two tests were conducted: test with constant and no trend and test with constant and trend.

The first test takes the form of the model  $(1 - L)y = b_0 + (a - 1)y(-1) + \dots + e$ .

1st order autocorrelation coefficient for  $e = 0.011$ , lagged differences:  $F(2, 113) = 14.796$  (0.0000), estimated value of  $(a - 1) = 0.0518326$ ,  $\tau_c(1) = -2.39326$  and asymptotic  $p$ -value = 0.1436.

The second test takes the form of model  $(1 - L)y = b_0 + b_1t + (a - 1)y(-1) + \dots + e$ .

1st order autocorrelation coefficient for  $e = -0.001$ , lagged differences:  $F(8, 100) = 4.779$  (0.0001), estimated value of  $(a - 1)$ :  $-0.0492756$ ,  $\tau_{ct}(1) = -1.64713$  and asymptotic  $p$ -value = 0.7743.

The results showed that a null hypothesis of the unit-root was rejected. Therefore, it was not necessary to difference the time-series for the ARIMA model. Using the autocorrelation function and partial autocorrelation function, the authors identified the ARIMA model to be ARIMA(1,0,1). Definitions of the roots lead to estimation of an ARMA(1,1) model.

The results in Table 6 show that both roots were significant. Hence, this test can be used for the prediction of the future price of palm oil, which will provide guidance for *Jatropha curcas* oil prices. This prediction is graphically given in Figure 5 for the next two years.

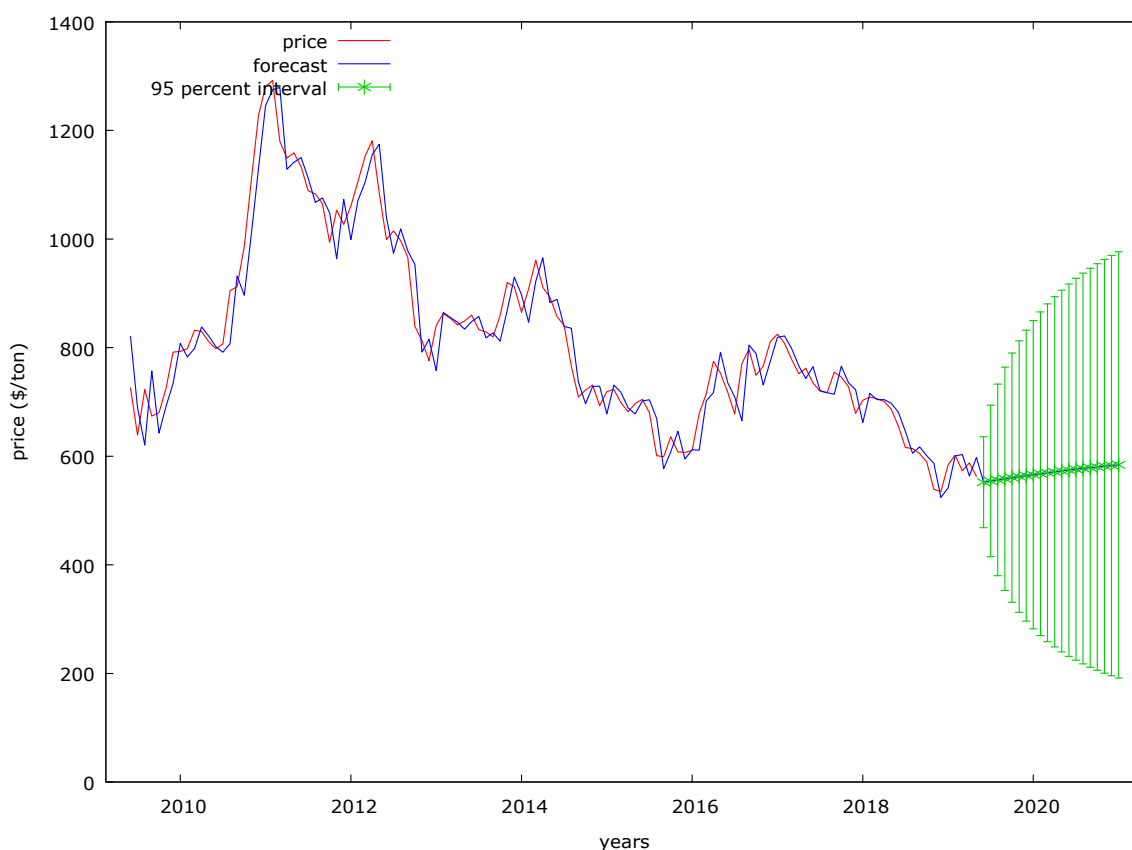
**Table 6.** Results of ARMA model.

|         | Coefficient | SD        | $z$   | $p$ -Value             |
|---------|-------------|-----------|-------|------------------------|
| const   | 627.468     | 115.799   | 5.419 | $6.01 \times 10^{-8}$  |
| phi_1   | 0.971330    | 0.0138850 | 69.96 | 0.0000                 |
| theta_1 | 0.360203    | 0.0516843 | 6.969 | $3.19 \times 10^{-12}$ |

Source: Own results.

The price ranges from \$552 per ton to \$584 per ton. The results of the prediction for the next 24 months show that the palm oil price has probably reached a bottom at \$552 per ton and a slight growth can be expected in the coming months. Given the uncertainty of the prediction (green shaded 95% interval), a middle value of \$568 was then used for the economic analysis of *Jatropha curcas* biogas powerplant profitability. When using the predicted price one must be cautious, as it is important to take into account other fundamental factors which may influence the price, such as prices of substitutes, etc.

Using all the aforementioned analytical results, the authors calculated the payback period, net present value, and break-even point.



**Figure 5.** Prediction of future price for palm oil. Source: Own results.

Payback period in Table 7 shows a relatively good outcome. Results could be even better if we assumed rising price of electricity. It is, however, important to be cautious as some of the assumptions are relatively strong. For example, it is assumed that CO<sub>2</sub> allowances will not be paid for by the power plant.

**Table 7.** Results of the economic analysis of biogas generation.

| Model Variable                  | Result  |
|---------------------------------|---------|
| Payback period (years)          | 7.91    |
| Break event point, volume (MWh) | 123,358 |

Source: Own results.

Finally, net present value was also calculated for different discount rates. The result of this analysis is presented in Figure 6. The shaded area in the diagram contains 80% confidence interval.

The results show that net present value is mostly positive for discount rates ranging from 1 to 11%. If the prevailing discount rate 8% is taken in account, NPV is positive in the entire interval of prediction. It is obvious that the price of *Jatropha curcas* or palm oil has a large impact on NPV.

The results presented in this paper are not discussed by many authors, as many studies focus on the use of *Jatropha curcas* seed and oil primarily for biodiesel production [51,71,72]. For example, Verma and Gaur [73] estimate the costs of production in the similar range.

A study by Bouffaron et al. [74] described the chemical process and economic model, but with uncertain conclusions for the viability of the project.

Other authors discuss energy investments in Indonesia. For example, according to [75], investment into diesel replacement with palm oil showed positive net present values and quicker payback period than the project analyzed in this paper. For China, Deng et al. [76] calculated the cost efficiency of

*Jatropha curcas* biodiesel with positive results albeit with a smaller discount rate. Use of biofuels was also discussed for Germany and the United States [77–79].

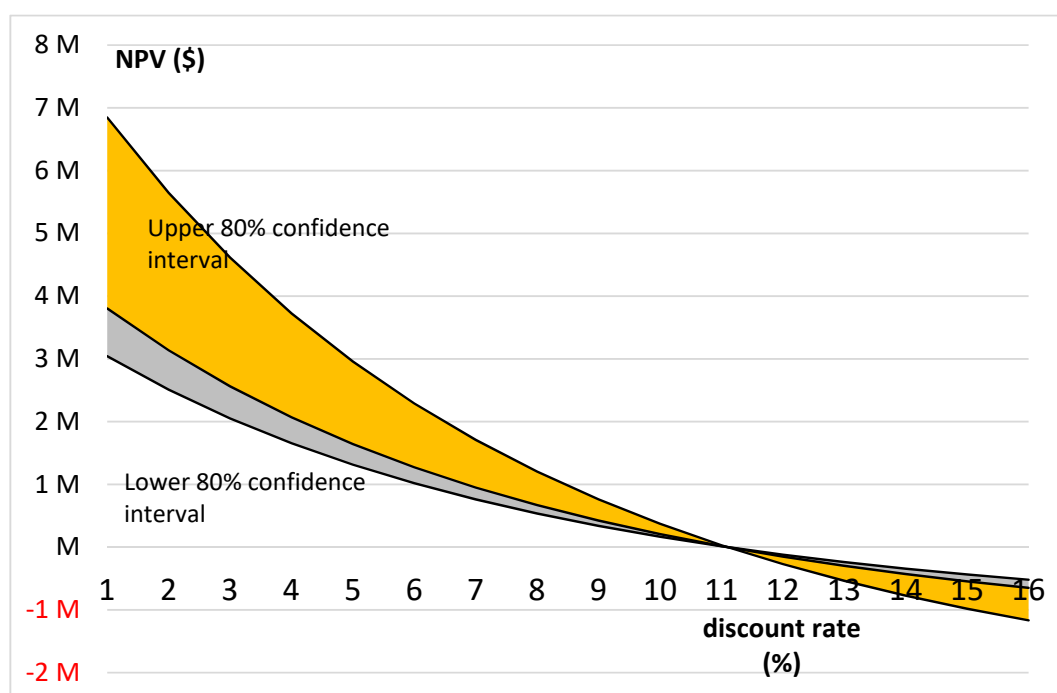


Figure 6. Net present value calculations. Source: Own results.

## 5. Conclusions

Our results provide a unique analysis of how to utilize byproducts from *Jatropha curcas* production in the form of cake and mesocarp. We propose utilization of these byproducts for electric power plants making it an excellent source of cheap electricity and an essential element in high renewables electricity systems. We quantified all the cost and benefit components of the project and set important parameters for their calculation including a floating discount rate. Viability of this venue was calculated. All profitability indicators used in the analysis showed very promising results. *Jatropha curcas*, based on this analysis, may be a very successful crop for biogas production. It would be, however, important to also evaluate other impacts of this project in terms of its social and environmental impact by incorporation of, for example, emission allowances.

The analysis presented in the paper shows that using byproducts of *Jatropha curcas* may be profitable. For some of the processors this can be a method of diversifying their businesses to use the byproducts of *Jatropha curcas* seed production. In terms of circular economy, the proposed use of *Jatropha curcas* mesocarp and cake in electricity production is also beneficial as it provides great benefits and contributes to a lower waste burden. All of these features make *Jatropha curcas* a novel and interesting element in a highly renewable electricity system.

**Author Contributions:** P.P., L.S. and V.H. designed methodology; P.P., L.S. and V.H. performed the calculation and analyzed the data; P.P., L.S. and V.H. wrote the paper.

**Funding:** This research was funded by Internal Grant Agency (IGA) of Faculty of Economics and Management, CULS Prague, grant number 2019B001.

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

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