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# Energy Opportunities from Lignocellulosic Biomass for a Biorefinery Case Study

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**Abstract:** This work presents some energy considerations concerning a biorefinery case study that has been carried out by the CRB/CIRIAF of the University of Perugia. The biorefinery is the case study of the BIT3G project, a national funded research project, and it uses the lignocellulosic biomass that is available in the territory as input materials for biochemical purposes, such as *cardoon* and *carthamus*. The whole plant is composed of several sections: the *cardoon* and *carthamus* seed milling, the oil refinement facilities, and the production section of some high quality biochemicals, i.e., bio-oils and fatty acids. The main goal of the research is to demonstrate energy autonomy of the latter section of the biorefinery, while only recovering energy from the residues resulting from the collection of the biomass. To this aim, this work presents the quantification of the energy requirements to be supplied to the considered biorefinery section, the mass flow, and the energy and chemical characterization of the biomass. Afterwards, some sustainability strategies have been qualitatively investigated in order to identify the best one to be used in this case study; the combined heat and power (CHP) technology. Two scenarios have been defined and presented: the first with 6 MWt thermal input and 1.2 MWe electrical power as an output and the second with 9 MWt thermal input and 1.8 MWe electrical power as an output. The first scenario showed that 11,000 tons of residual biomass could ensure the annual production of about 34,000 MWht, equal to about the 72% of the requirements, and about 9600 MWhe, equal to approximately 60% of the electricity demand. The second scenario showed that 18,000 tons of the residual biomass could ensure the total annual production of about 56,000 MWht, corresponding to more than 100% of the requirements, and about 14,400 MWhe, equal to approximately 90% of the electricity demand. In addition, the $CO_2$ emissions from the energy valorization section have been quantified and the possibility of re-using the $CO_2$ flow in order to produce methane is described.

**Keywords:** biorefinery; sustainability; *cardoon*; *carthamus*; energy recovery

## 1. Introduction

Biorefineries can be classified on the basis of several parameters, such as the type of technology used, and in this case, they are named as a biorefinery of first, second, or third generation. Depending on the chemical composition of the raw material used as the input, we can also classify them as lignocellulosic biorefineries, "green" biorefineries, and marine biorefineries. Another possible classification can be done on the basis of the type of the intermediate products and biochemicals obtained in the biorefinery, and in that sense, the classification is related to both the involved sugar platforms and the energy carriers used.

One of the most common classification systems concerns the type of conversion processes used, in this case being thermochemical and/or biochemical biorefineries [1–7].

Furthering the analysis of the classification methodologies for biorefineries, the scientific community is focusing on several aspects such as biorefinery logistics [8,9], the type and quality of the produced biochemicals [10,11], and the overall environmental impacts [12].

Energy recovery from residues, used to cover the requirements of the biorefinery processes, is an interesting task to be further explored since it is often discussed separately. The production of energy from lignocellulosic residual biomass has long been investigated [13] and demonstrated [14], however the progress in energy sustainable technologies still has to be largely applied to the biorefinery concept.

This paper considers the case study of a biochemical biorefinery, using as an input feedstock both *cardoon* and *carthamus* and producing oil derived by-products as outputs.

The scope of this work is to achieve energy autonomy of one section (the section producing biochemicals) of the considered biorefinery using the lignocellulosic residual biomass that results after harvesting and collection. This paper describes the methodological steps needed to fulfill this objective; it starts with the evaluation of the energy requirements of the biorefinery and then proceeds with the mass flow and energy characterization of the biomass. Afterwards, some possible energy recovery technologies are considered and the most suitable option for the case study is selected and dimensioned. Finally, some environmental considerations are discussed concerning the reuse of $CO_2$ through the Sabatier process.

This paper establishes a novel methodology as a pre-step to analyze the energy requirements within the biorefinery concept on the basis of modeling tools [15,16], instead of analyzing real case studies of plants that are already functioning in the environment.

## 2. Energy Requirements

Figure 1 shows the scheme of the biorefinery concept. It starts with the collection of the lignocellulosic biomasses (*cardoon* and *carthamus*) that is harvested and conveyed to the oil seeds extraction and oil refinement phases. Afterwards the refined oil goes to the production section of the monomers, which allows for the production of high quality biochemicals. After harvesting the *cardoon* and *carthamus* biomass, there is a need to collect the residues: *cardoon* and *carthamus* stalks.

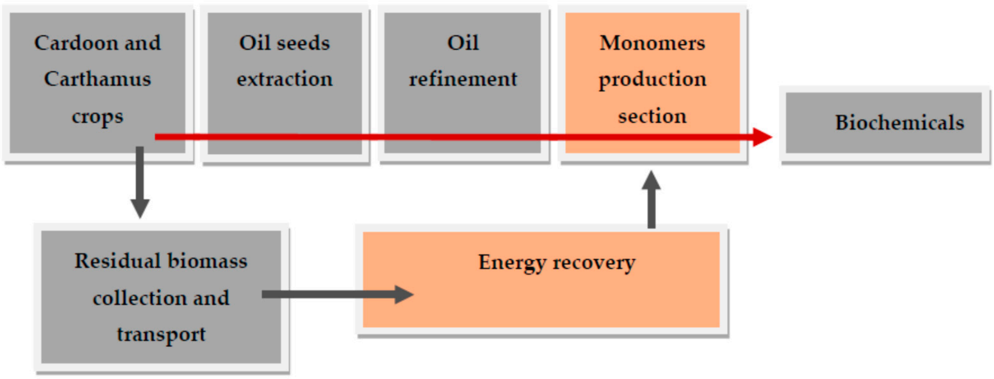


**Figure 1.** Biorefinery concept: seed path (in red) and residual stock path (grey).

This study presents an energy strategy to cover the energy requirements of the production section of the monomers (orange colored) using this type of residual biomass resulting from the collection phases.

In this context, the data related to the energy needs (electrical and thermal) of the monomer production plant were first acquired. These data were provided by project partners within the BIT3G project, a research project coordinated by Novamont and funded by the Italian Ministry of Education and Research.

In particular, the energy requirements of the production section of monomers consists of a combined demand of electrical energy that is approximately equal to 16,700 MWh/year and of thermal energy that is approximately equal to 47,500 MWh/year. This energy is used to produce up to 25,000 t/year of oil with a high oleic content at 310 °C.

## 3. Mass Flow and Energy Characterization

Starting with the energy requirements of the biorefinery, the potential energy obtainable from the residual biomass was estimated, in order to demonstrate the possibility of supplying energy to the biorefinery exclusively through its energy enhancement. For this purpose, the data yields of the average aboveground biomass per hectare (*cardoon* and *carthamus*) were adopted as the input to the energy evaluations. These data were provided by project partners within the BIT3G project, while the unitary energy potential of the biomass was measured in the laboratory of the Biomass Research Center (CRB) of the University of Perugia.

Table 1 shows the characteristic values used for the dimensions of the energy recovery section of the residual biomass and Tables 2 and 3 report the chemical characterization and the component description of the lignocellulosic residual biomass. The lab measurement procedures used for the characterization follow the international standard regulations and they are already described in previous works [17].

**Table 1.** Average values of the *cardoon* and *Carthamus* growing yield for a hectare per year (provided by project partners within the BIT3G project) and their energy content (measured at the CRB/CIRIAF Lab).

| Type of Residual Biomass | Residual Biomass Availability | Energy Content of Residual Biomass |
|---|---|---|
| *Cardoon* | 13.2 t/ha [1] | 4.5 kWh/kg |
| *Carthamus* | 1–1.5 t/ha [1] | 4.1 kWh/kg |

[1] average hectare yield.

**Table 2.** Chemical characterization of the residual biomass (*cardoon* and *carthamus*) carried out by the CRB/CIRIAF Lab.

| Type of Residual Biomass | Water Content | Wet Basis | | | Dry Basis | | |
|---|---|---|---|---|---|---|---|
| | | C | H | N | C | H | N |
| *Cardoon* | 6.68% | 42.25% | 6.00% | 0.22% | 45.03% | 6.39% | 0.23% |
| Standard deviation | 0.12% | 0.35% | 0.62% | 0.12% | 0.38% | 0.66% | 0.13% |
| *Carthamus* | 6.57% | 45.00% | 6.60% | 0.30% | 47.96% | 7.03% | 0.32% |
| Standard deviation | 0.21% | 0.14% | 0.05% | 0.16% | 0.15% | 0.05% | 0.17% |

**Table 3.** Components of the lignocellulosic residual biomass measured by the CRB/CIRIAF Lab.

| Type of Residual Biomass | Hemicelluloses | Cellulose | Acetyl Groups | Lignin | Extractives | Ashes |
|---|---|---|---|---|---|---|
| *Cardoon* | 15.86% | 32.66% | 5.21% | 16.53% | 9.50% | 6.50% |
| Standard deviation | 0.08% | 0.17% | 0.02% | 1.16% | 0.00% | - |
| *Carthamus* | 14.28% | 29.21% | 4.99% | 19.61% | 12.19% | 3.63% |
| Standard deviation | 0.23% | 0.30% | 0.03% | 0.23% | 0.00% | - |

Both the energy and chemical characterization of the residual biomass (*cardoon* and *carthamus*) showed that these two types of matrices are almost comparable in terms of higher heating values, cellulose, lignin, and hemicelluloses. In addition, similar values of the main components are obtained in other lignocellulosic residues in spite of having less cellulose content in this case [10,13,18].

This aspect allows us to make the evaluation of the mass flow as an input to the plant as well as the biomass, since the scope of the energy evaluations is simply to define the order of magnitude of the biomass streams.

## 4. Possible Energy Recovery Strategies

Once the potential for the mass and energy obtainable from the recovery of the aboveground biomass was quantified, we proceeded to evaluate the possibility of using different energy recovery technologies. The study involved the analysis of different technologies with the identification of the relative critical issues [19–26]. In summary, the considered possibilities concerned the use of:

(1) anaerobic digestion technology;
(2) gasification technology;
(3) a cogeneration system (CHP-Combined Heat and Power) working at high temperature.

Anaerobic digestion is a stable and consolidated technology that allows for energy recovery from residues; however, an analysis of the characterization features of the residual biomass mainly shows that the residues of *cardoon* and *carthamus* are not adequate for this purpose because of their low cellulose content. This aspect represents a strong limitation for the application of this solution for the considered biorefinery, as anaerobic digestion is conventionally carried out with high efficiency on sugary and starchy substrates. However, the application of anaerobic digestion technology to the lignocellulosic matrices represents a line of research and innovation that is active at the CRB University of Perugia [27], but it should be further investigated before application. This line of research involves the use of lignocellulosic biomass in the system of co-digestion with other sugary and starchy substrates, after the appropriate physical pretreatment of steam explosion, thus providing an efficient strategy to feed biogas plants with a smaller flow coming from dedicated energy crops, and not potentially in conflict with the food chain. However, this is considered to be an initial analysis, and this solution is not very suitable for potential use in the context of the BIT3G biorefinery project.

Gasification technology represents a possible energy recovery strategy of the residual biomass, but it appears to be mainly applicable in the case of woody biomass use with a homogeneous morphology and characterized by an almost constant energy content. In fact, several case studies of these operating systems are established in Northern Europe and in geographical areas with the relevant availability of wood. For this reason, it was considered not appropriate to use this energy recovery solution for the biorefinery.

The most suitable energy technology proposed for this case study is the CHP cogeneration system with an ORC (Organic Rankine Cycle) turbine operating with thermal oil, allowing for the combined production of electricity and heat.

This system layout also seems to be appropriately applicable for this case study considering the relationship between the electricity and thermal energy requirements of the biorefinery.

Furthermore, this technology can obtain the thermal energy at a high temperature (approximately 300 °C), as required by the section producing the monomers. The aboveground biomass, once collected, has to be appropriately pretreated in order to achieve its dimensional homogenization. After considering these aspects, we proceeded to design two possible energy scenarios, each one with the proper quantification of mass and energy flows.

In summary, the CHP technology has been considered as the most appropriate option for this case study for the following reasons:

We deduced from the chemical characterization that the lignocellulosic biomass is not suitable for anaerobic digestion by itself, since the measured cellulose content is not so high. This conclusion is in agreement with previous reports in the literature [28].

The physical heterogeneity of the residual biomass is not suitable for gasification technology, that is conventionally used for woody and homogeneous biomasses mainly diffused in Northern Europe [29].

The ratio between the thermal and electrical requirements of the biorefinery case study is similar to the thermal and electrical power that can be provided by the CHP technology as declared in the technical data sheets of the technology [30].

## 5. Methodology and Energy Calculations

The thermal input to the CHP plant has been determined following Equation (1) on the basis of the average energy content of residual biomass as measured and reported in Table 1. Afterwards, the average collected flows of the residual biomass (in tons/year) have been estimated, allowing the production of the fixed thermal input. Secondly, after assuming that the annual functioning hours for the CHP plant is equal to about 8000 h, both the producible thermal and electrical energy have been determined. In this calculation, the typical conversion efficiency from thermal to electric energy of the CHP module has also been considered, and this value is equal to 20% for the chosen technology.

$$TI_{CHP} = (EC \times CB)/H \quad (1)$$

in which:

- a $TI_{CHP}$ is the thermal input to the CHP plant in MWt;
- b EC is the energy content of the residual biomass in kWht/kg;
- c CB is the annual flow of the collected residual biomass to be used as the input to the plant in tons/year;
- d H is the number of the annual functioning hours for the CHP plant in hours/year.

The first scenario (SCENARIO 1), that is shown in Figure 2, is composed of a CHP module operating with a thermal input equal to about 6 MW and with an electrical yield equal to about 1.2 MWe.

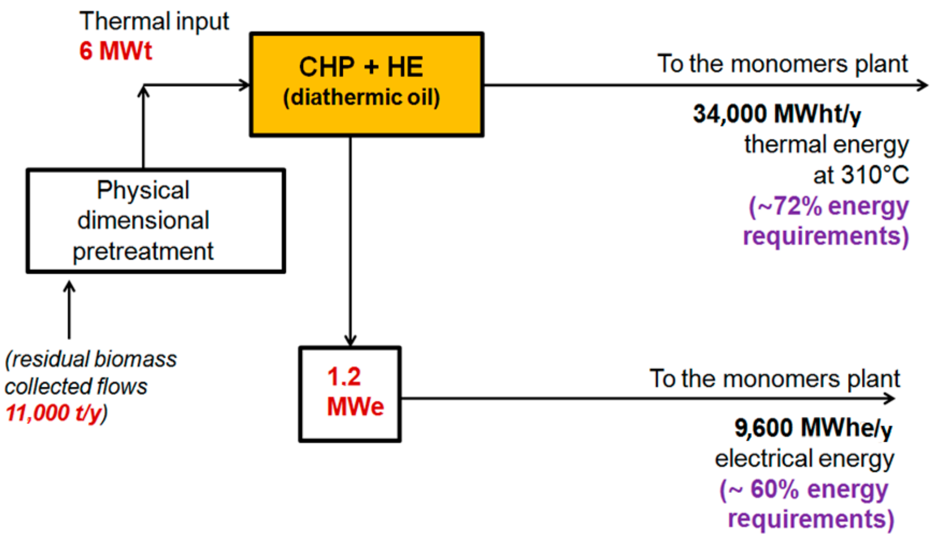


**Figure 2.** SCENARIO 1-Energy recovery from the residual biomass (*cardoon* and *carthamus*).

For this configuration, the thermal input for the plant can be ensured by an annual intake of about 11,000 tons of the aboveground biomass (suitably pre-treated), and in total the plant could ensure the annual production of about 34,000 MWht available at 310 °C, equal to about 72% of requirements and about 9600 MWhe, equal to approximately 60% of the electricity demand.

Since that the associated configuration of SCENARIO 1 can only cover part of the energy requirements of the biorefinery, we proceeded further with the assumption of employing a co-generation plant with a higher thermal input (Figure 3, -SCENARIO 2).

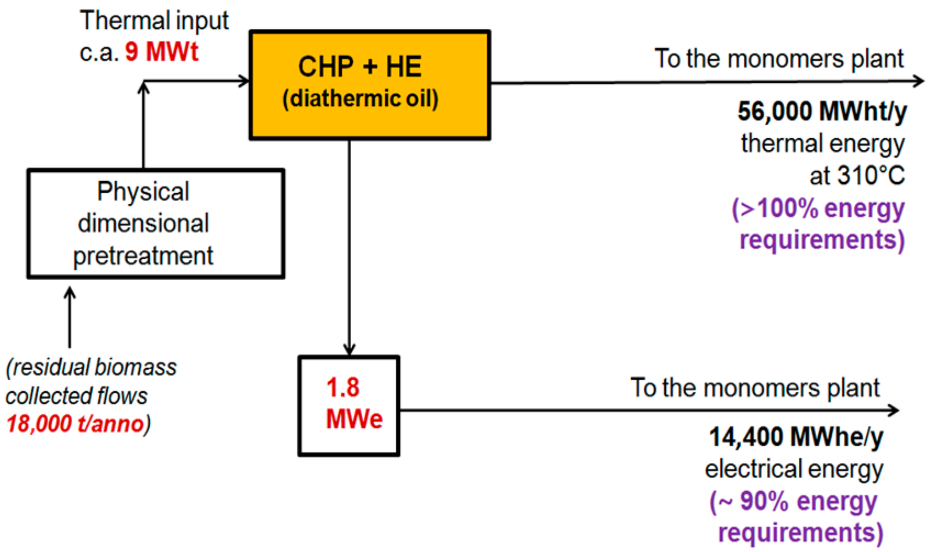


**Figure 3.** SCENARIO 2-Energy recovery from the residual biomass (*cardoon* and *carthamus*).

In this second case, a surplus of thermal energy produced would be available at 310 °C, which should find alternative uses within the biorefinery.

In particular, tSCENARIO 2 is composed of a CHP module operating with a thermal input equal to about 9 MW and with an electrical yield equal to about the 1.8 MWe.

In this case, the thermal input to the system can be ensured by an annual intake of about 18,000 tons of aboveground biomass and the plant could ensure the total annual production of about 56,000 MWht available at 310 °C, corresponding to more than 100% of the requirements and of about 14,400 MWhe, equal to approximately 90% of the electricity demand.

These evaluations are mainly in agreement with other similar studies reported in the literature [31,32], even though there are not so many studies regarding biomasses CHP powered plant.

Concerning economics, a complete evaluation that includes all sections of the biorefinery and not only the facility for producing monomers should be carried out. However, the scope of this work was only limited to the dimensioning of the energy recovery section, which allows for the supply of energy for the biochemical section and not for the whole plant.

Despite this, some economic costs can be disclosed, i.e.,

a the investment costs for the installation of a 6–9 MWt and a 1.3–1.8 MWe CHP plants vary between 4.0 and 6.0 M€ [33];
b the operating costs can be estimated annually as about 5% of the investment costs;
c the costs for the biomass is only related to the logistical and transportation costs, and it depends on the biomass availability distribution;
d the revenues for the plants should be evaluated accordingly with the incentive system after subtracting the net thermal and electrical energy requirements.

Moreover, regarding the electrical energy that is producible by the CHP plant of SCENARIO 2, 90% of the electricity requirements for the biochemical section of the biorefinery are produced by renewable energy, which allows for monetary savings of about 2.8 M€/year (considering that 0.22 €/kWhe is the current value of electricity from the Italian grid).

## 6. Quantification of the $CO_2$ Emissions and Its Possible Use

To further quantify the energy demand and supply of the considered plant section of the biorefinery, we quantified the carbon dioxide emissions of the chosen technology in order to evaluate the possibility of capturing and using the $CO_2$ flux. To this aim, the following table (Table 4) reports some carbon emission values, which refers to the CHP technology but also considers a natural gas powered plant. Some hypotheses have also been carried out, allowing us to quantify the $CO_2$ emissions in the case of residual biomass (*cardoon* and *carthamus*) feeding the CHP plant.

The carbon dioxide emission factors refer both to the unitary thermal energy and electrical energy. The first hypothesis concerns the evaluation of the carbon dioxide for a biomass fed plant instead of natural gas: in this case, we have applied an increased coefficient to the $CO_2$ flux for natural gas that is equal to 1.30. This evaluation arises from past studies carried out by the Italian CRB and also previous literature [25,26]. The second hypothesis concerns the evaluation of the $CO_2$ flux purity resulting from the CHP plant: in the case of natural gas feeding, the outgoing $CO_2$ flux is almost pure while in the case of lignocellulosic biomass feeding, the outgoing $CO_2$ flux needs to be purified by means of separation technologies. In the second case, a decreased coefficient to the $CO_2$ flux has to be applied. We estimated a decreased coefficient to the $CO_2$ flux equal to about 0.7: this evaluation arises from the past studies carried out by the Italian CRB in $CO_2$ separation technologies [34].

**Table 4.** $CO_2$ emission factors and adapting coefficients applied to the case of CHP fed by lignocellulosic biomass (IPCC 2014 [35] *).

| Carbon Dioxide Emission kg $CO_2$/MWhe | Carbon Dioxide Emission kg $CO_2$/MWht | Fuel | A ** | B *** |
|---|---|---|---|---|
| ~230 | ~920 | Natural gas | ~1.30 | ~0.7 |

* IPCC, report 2014, Global warming potential of selected electricity sources. ** Increased coefficient for the $CO_2$ emissions in the case of a lignocellulosic biomass input instead of natural gas. *** Decreased coefficient for the $CO_2$ emissions considering the average efficiency of the $CO_2$ separation technologies.

Furthermore, the possibility to produce methane from the quantified $CO_2$ flux has been considered. To this aim, the Sabatier process i.e., the solar gas technology, has been applied. The solar gas technology was tested by the University of Perugia [36] during the implementation of the BIT3G project. This technology allows to produce methane from a $CO_2$ pure flux and from a $H_2$ pure flux, using organic catalysts. The $H_2$ flux is obtained from the electrolysis of water, achieved by electricity from PV or from other sources. The reaction Equation (2) is the basis of solar gas technology.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O\,(\text{with catalysts}) \tag{2}$$

230 kg/h of $CO_2$ and about 64 $m^3/h$ $H_2$ are required to produce up to 95 $m^3/h$ $CH_4$.

This calculation, applied to SCENARIO 2 (Figure 3), shows that for 1.8 MWe (considering 1 h functioning time), 414 kg/h of $CO_2$ and about 115 $m^3/h$ $H_2$ are required to produce 170 $m^3/h$ $CH_4$. This calculation can also be applied to SCENARIO 1.

## 7. Conclusions

This paper presented the results regarding energy considerations for the case study of the biorefinery of the BIT3G research project. The work showed that energy autonomy of the monomers production section can be achieved by obtaining thermal and electrical energy from the residual biomass resulting from the collection of the *cardoon* and *carthamus* crops. The energy requirements for the biochemical production section of the biorefinery is a combined electrical energy demand of approximately 16,700 MWh/year and a thermal energy demand of approximately 47,500 MWh/year to achieve a production capacity of about 25,000 t/year of high oleic oil with diathermal oil at 310 °C.

The energy and chemical characterization of the biomass flows showed that the energy content for *cardoon* and *carthamus* is between 4.1 and 4.5 kWh/kg and that the average chemical composition of the two matrices is almost comparable.

The overview of the existing technology for energy production indicates that the CHP technology is the most suitable for this application. On the basis of previous results, two scenarios were considered and presented: the first with 6 MWt thermal input and 1.2 MWe electrical power as an output, and the second with 9 MWt thermal input and 1.8 MWe electrical power as an output.

In addition, carbon dioxide quantification has been carried out, which also presents the possibility of using the $CO_2$ flux to produce methane, by means of solar gas technology and the Sabatier process.

The future direction of this work is to evaluate the positive environmental effects caused by providing all the energy requirements for the biorefinery from the biomass residues. This aspect is currently under investigation using the life cycle assessment (LCA) approach. Furthermore, the environmental impact of the logistics of transport and collection of the biomass will also be quantified.

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**Author Contributions:** Franco Cotana coordinated the research, Valentina Coccia wrote the article, Gianluca Cavalaglio and Alessandro Petrozzi coordinated and carried out the lab measurements.

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

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| BIT3G project | Italian acronym for "Third generation biorefinery spread in the territory" |
| CRB/CIRIAF | CRB is the acronym for National Biomass Research Center. CRB is a section of the CIRIAF that is the Interuniversity Research Center of Pollution and Environment "M. Felli" of the University of Perugia |

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