TECHNO-ECONOMIC STUDY OF AGROVOLTAIC SYSTEMS FOCUSING ON ORCHARD CROPS

Brecht Willockx, Bert Herteleer and Jan Cappelle
Research Group Energy & Automation, KU Leuven
Brecht.willockx@kuleuven.be, Gebroeders De Smetstraat 1, 9000 Gent, Belgium

ABSTRACT: This paper presents a novel 3D agrovoltaic modelling tool developed in python which enables technical and economical evaluation of potential agrovoltaic designs. It has been designed and applied for fruit crops which typically have a crucial flowering period. To illustrate the potential of this tool, a case study for pear trees in Bierbeek, Belgium is shown. While many geometrical parameters of agrovoltaic systems are fixed in practice, however, there is also the need to model the impact of PV modules on the tree light interception. The results of the modelling show that the amount of solar radiation depends on the modules used, with semi-transparent modules offering better light distribution and reduced crop loss. Based on the modelling, a prototype agrovoltaic set-up with pear trees and semi-transparent modules has been built in Bierbeek, Belgium.

Keywords: Simulation, economic analysis, semitransparent modules, agrivoltaics, Agro-PV

1 INTRODUCTION

While the growth of photovoltaic (PV) installations worldwide is expected to continue in the coming years due to its rapidly reduced cost and impact on decarbonizing the electricity grid, PV systems are running into social license issues in areas with constrained availability or high-value land. One possible solution for this is agrovoltaic systems [1], which combine crop growth and the production of photovoltaic energy on a single site. These dual land use systems are attractive in land-constrained environments; however, the concept has also proven to be successful in protecting crop development for (semi)-arid and dry regions [2].

Most of the studies (with exception of the Sun'Agri program [3]) that were carried out have focused on field crops with a lower economical market value such as cereals and potatoes [4]. Little attention has been paid to studies with orchard crops (fruits and nuts). This can partly be explained by the fact that most orchard crops require much sunlight for crop production and show limited shade tolerance. However, many benefits from using agrovoltaic systems with orchard crops can be found:

Orchard crops:

- Require smaller machinery or employ manual labor resulting in smaller spans and potentially lighter and cheaper PV agrovoltaic structures;
- Do not have a yearly rotation, one site is used for one type of crop for more than 20 years;
- Are placed in regular rows, where PV modules can offer optimal protection against wind, heavy rain, hail and sunburn and replace current temporary plastic protections;
- Often require cooling for on-site storage post-harvest, which increases the self-consumption rate and improves the business case;
- Have a higher economical market value resulting in a better balance with the economic value of the generated energy.

Also noticeable in academic research is the little information how agrovoltaic installation should be designed, with a focus on 2D software to see the PV impact on the crop light interception. The purpose of this work is to develop a techno-economic design methodology for orchard crops based on practical design considerations for an agrovoltaic installation (tilt, height,…). Additionally, a more detailed 3D agrovoltaics light interception model is created where different PV types (opaque, semi-transparent) can be integrated.

The proposed design methodology and 3D model is applied on a case study within the Flemish TETRA Agrivoltaics project. The chosen static PV configuration and PV type was built in August 2020 and will be used to calibrate model parameters in the following years on the basis of measurements on the PV energy yield, crop yield and crop quality characteristics.

2 BACKGROUND

2.1 Project description

The high population density and limited open space in Belgium has led to the Flemish TETRA Agrivoltaics project, which started in October 2019 and is financed by the Flemish government and SMEs. The purpose of this two-year project is to investigate the agrovoltaics potential in Flanders.

The intention is to design four different agrovoltaic installations, which are sufficiently diversified according to crop- PV- and construction type. After an initial literature study, four suitable locations were identified for test agrovoltaic systems to be installed in Flanders. The installations will be equipped with state of the art measuring instruments to collect sufficient microclimatic, electrical and crop technical parameters. A comparison of the installations will be made at the end of the project in function of economic, electrical and agricultural yields/quality.

2.2 Case study

One of the selected locations is situated in Bierbeek, Belgium (Latitude: 50.819 ºN; Longitude: 4.775 ºE) where orchard crops (apple and pears) are cultivated. A schematic representation the pear orchard can be found in Figures 1 and 2. The pear trees (cultivar *conference*) are 2.4 m high, oriented South East (with a deviation of 30° from the South), have a planting distance of 1 m and an inter-row distance of 3.3 m.

The agricultural site has also storage rooms with adequate refrigerating capacity. It is assumed that the greatest cooling capacity is requested during summer until September - October, after the harvest of the pears. By contrast, cooling load during winter months is rather limited.

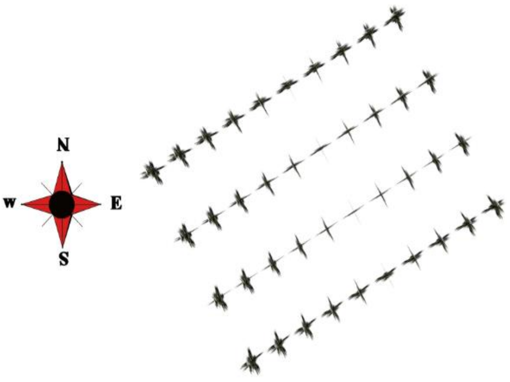

Figure 1: Orientation of the pear orchard for the agrovoltaic test site.

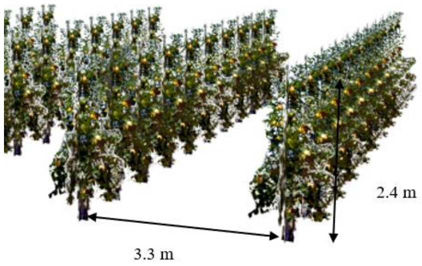

Figure 2: Pear orchard typical dimensions.

3 PRACTICAL AND FINANCIAL DESIGN CONSIDERATIONS

This works assumes that the priority in agrovoltaic systems is given to food production while the energy production is a secondary added value. Theoretically, agrovoltaics is a typical example of a multi-objective optimisation problem, where both energy- and crop (quality) yields depend on the PV geometrical parameters (height, tilt, inter-row distance, …). However, this case study will show that most geometrical parameters are constrained by practical and financial considerations.

3.1 PV type and PV structure

The PV type used in this design approach is based on mature PV technologies (silicon PV cells sandwiched between glass plates), where more advanced technologies (perovskite, spectrum splitting foils,…) are not yet considered as economically viable.

Since agrovoltaic structures are placed in an agricultural area, temporary anchors or pillar drilling systems without any permanent concrete fixation are favoured. These temporary fixations are in most cases less resistant to the high and exponential wind lift forces, require a complex installation, and are more expensive. This explains the need for a PV structure that limits the wind load. A double-sided fixed inclined PV structure has been chosen based on wind load standard NBN EN 1991-1-4 [5] which roughly halves the local wind load coefficients in comparison with a single-sided inclined PV structure. Additionally, the decreased wind load results in smaller and lighter structure components, making the PV structure more cost-effective.

3.2 Geometrical design

The South East orientation and inter-row distance of the PV structures are already defined based on the position of the rows of the pear orchard (generally the field direction). It is advisable in Belgium to place the PV modules above the trees to ensure the required protection against heavy rain and hail as can be seen in Figure 3.

The height of the PV structure is chosen in function of the dimensions of the agricultural machinery (e.g. orchard sprayer), and is not further increased considering the additional material costs and exponential fixation costs together with increased visual landscape pollution.

The remaining geometrical parameter is the tilt angle, which most of the times will be kept small to decrease the chance of module self-shading and to increase the production of energy during September and October, improving the self-consumption rate. Additionally, this small tilt reduces the wind load and increases the fruit protection.

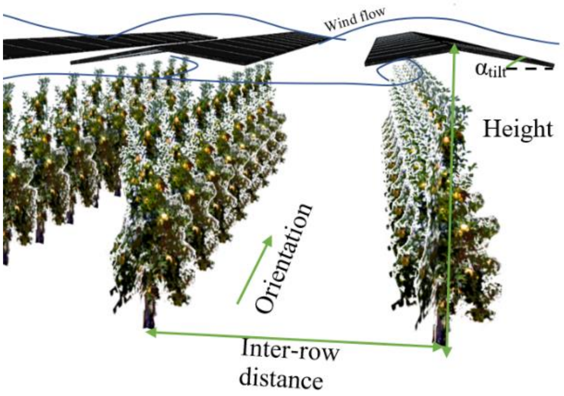

Figure 3: Geometrical parameters of the agrovoltaic structure. A double-sided inclined configuration is chosen to limit the wind load.

4 THE NEED FOR A 3D AGROVOLTAIC MODEL

When all geometrical parameters are chosen, there is still the question of the PV ground coverage ratio (GCR = module area/land area, expressed in percent). A higher GCR will result in more energy production but also limits the sunlight interception and consequently the number of pears and pear growth (and vice versa for a lower GCR). A simple and basic methodology to quantify the impact of the GCR on the light interception does not exist, considering the complex 3D shape of the pear trees and the time and spatial varying shade/solar intensity of the sun.

This work proposes a 3D agrovoltaic simulation model based on the OpenAlea framework [6]. OpenAlea is an open source project created by INRA, focusing on plant modelling. It is a collaborative effort to develop Python libraries and tools that address the current and future needs in plant modelling. This work uses the VPlants component, which exist out of packages to analyse, model, simulate and visualise (PlantGL) plant architectures. This work extends the VPlants package with a PV structure node, where PV modules can be added to the 3D scene. The 3D agrovoltaics model is written graphically as dataflow in the Visualea environment.

4.1 Creation of the virtual pear trees

The Weber and Penn algorithm [7] has been applied to create virtual pear trees. This model uses some basic geometrical parameters (height, number of branches, branch angles, leaf density, ...) in order to simulate the complex 3D shape. The virtual pear trees, visualised in PlantGL in Figure 4, are based on geometrical observables from the Bierbeek site. These pear trees have typically sharp branch angles (from 30° to 75°) and obtuse leaf angles.

Figure 4: Example of a pear tree creation by the Weber and Penn algorithm shown in the PlantGL viewer.

4.2 Light interception

Actual light interception properties of the trees were computed from the 3D virtual plants by the use of the VPlants Fractalysis package. The directional light interception is based on computation of the projected leaf area by processing pictures of the 3D scene in the sun's direction Ω. Indeed, the scene elements seen on the directional picture are those who are lit from the sun. The amount of projected leaf area that intercepts the sunlight in direction Ω is calculated by counting the green leaf coloured pixels in the image. In this way, the tool takes into account the shading effects of other leaves, neighbouring trees and the PV modules.

The same methodology has been applied for the diffuse light interception, where leaf viewfactors are calculated based on a discretized sky hemisphere.

4.3 Agricultural yield

Pear trees rest in winter. On the branches are buds, some of them contain leaves and others contain flowers. The growing season starts around April: the leaf buds unfold and flower buds begin to grow. The integrated amount of received sunlight in this phase determines the number of flower buds that are later able for fruit setting, i.e. the number of fruits/tree. Too low radiation levels will result in less buds able to flower or flower buds that are not strong enough for fruit setting. Later, the pear tree will begin to turn the strong and pollinated flowers into fruits (i.e. fruit setting). Normally, pear trees set more fruit than needed. Therefore, they are thinned out to improve the fruit size and quality. Currently, there is no information available which expresses the received amount of solar radiation in function of the number of flowers capable of fruit setting (number of fruits). Also, it should be noted that a reduced number of flower buds results in a reduced need for out thinning. Considering both the relation solar radiation-number of flowers and the out thinning process, this work assumes a very primitive quadratic relationship, expressing the reduction of number of fruits after out thinning in function of the shading level (Figure 5). Note that this is an initial modelling assumption, where a more correct relation will be measured in in situ environments.

In summer, the pears grow bigger (g/fruit) until they are ready to harvest in September. This work assumes that the dry weight increase only depends on the received photosynthetically active radiation (PAR, roughly taken at 0.5 of the full solar spectrum) as the pear trees are irrigated and always get the perfect amount of water. The PAR light saturation point is situated around 225 W/m^2 [8], meaning that further increase of radiation levels not increase the CO_2 assimilation rate as shown on the light response curve in Figure 6. The positive impact of reduced leaf temperatures (due to the reduced solar radiation on the leaves) on the assimilation rate and the light response curve for shaded leaves are not yet integrated. Note that the assimilates are partly divided over the number of fruits which means that a decreased assimilation rate results on a reduced impact on the dry weight increase when the number of fruits are also decreased.

4.4 Agricultural quality

The more frequent heatwaves in Europe and Belgium led to higher chances of fruit sun burn and consequently a decrease in fruit quality. Fruit sun burn can be caused by high levels of UV radiation or too high fruit surface temperatures on windless and hot days. Both effects are strongly reduced due to the shade of the PV modules. The reduction of the high radiation levels within the pear trees is calculated to better evaluate the improved positive quality effects. More detailed quality aspects like fruit coloration, size, fruit firmness, starch and soluble sugars are in this phase difficult to express in function of the reduced solar radiation and are therefore not yet taken into account.

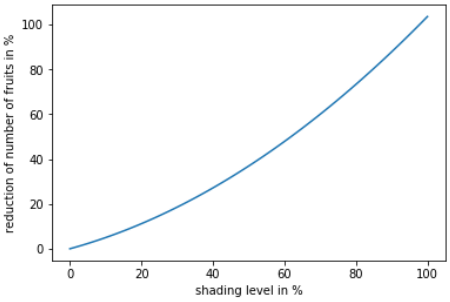

Figure 5: Relationship between shading level and reduction of number of fruits.

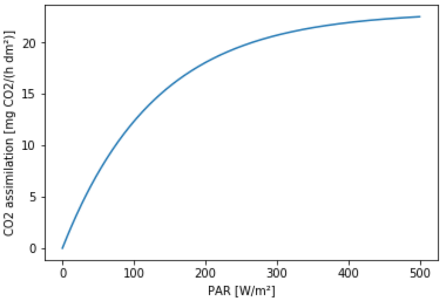

Figure 6: Impact of PAR light on CO2 assimilation rate of pear leaves, light use efficiency and saturation point from [8].

4.5 Energy yield

A prediction is made of the PV energy yield in parallel with the light interception raytracing algorithm. Perez's anisotropic model is used to calculate the irradiance on the PV modules. The DC and AC energy are estimated based on the PVWatts model from pvlib [9]. The PV cell efficiency is taken at 21%. Faiman's thermal model is used to take account of the higher PV module elevation and subsequent windspeeds.

5 RESULTS AND DISCUSSION

The 3D agrovoltaics simulation model is used to simulate different GCR options and PV types at the Bierbeek site. The geometrical parameters explained in section 3 are used, with an array height of 4.6 m. This is the minimum requirement based on the existing hail net protection and orchard sprayer used. The tilt of the modules is assumed at 12.5°, considering the wind load, module self-shading and module self-cleaning demands.

The hourly weather data for the simulation is obtained from the TMY generator created by the Joint Research Centre of the European Commission. While the energy yield is often expressed annually, the number of fruits is evaluated only for the month April. Additionally, the fruit weight is computed between May and September.

Averaged annual light interception values cannot be used due to the varying 3D shade fractions and the critical flowering period in April.

5.1 Without PV modules

It is assumed that, on average, a tree carries 100 pears with an average weight of 170 g per pear. The light interception of the trees is shown in Figure 7.

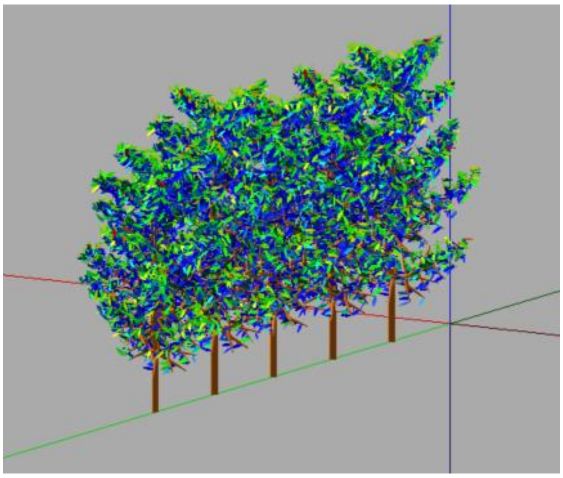

Figure 7.: Light interception of pear trees with the Fractalysis package.

5.2 Opaque modules

A first option for the considered PV system is to place opaque modules in landscape (as shown in Figure 3). This would result in a GCR of 60% and an energy yield of 245.62 kWh/tree. However, the light interception analysis shows an excessive reduction of pears (-40%) for the month April and additionally, a weight reduction of 25%. The limited number of (small) pears results in a skewed agrovoltaic system yield with an unacceptable crop decline.

One way to increase the light interception of the trees is a reduction in GCR. Because of the chosen commercial modules, it is not possible to further decrease the GCR in the transverse direction. Therefore, a checkerboard configuration in the longitudinal direction is selected. Places without PV modules can be replaced by plastic covers to sustain the required hail protection.

The GCR of 30% results in an energy yield of 121.85 kWh/tree (more cable losses). On average, there is a pear number reduction of 21% and a weight reduction of 15%. However, looking at the spatial distribution in Figure 8, there is clearly a division in sunlit and shaded areas. This means that the number of pears per tree varies a lot across the orchard and that they are growing/ripening at the different rate. This leads to practical issues, for example, it is not possible to harvest the field in one go. Note that the division in sunlit and shaded areas is the direct effect of the South East orientation and the large longitudinal module dimension.

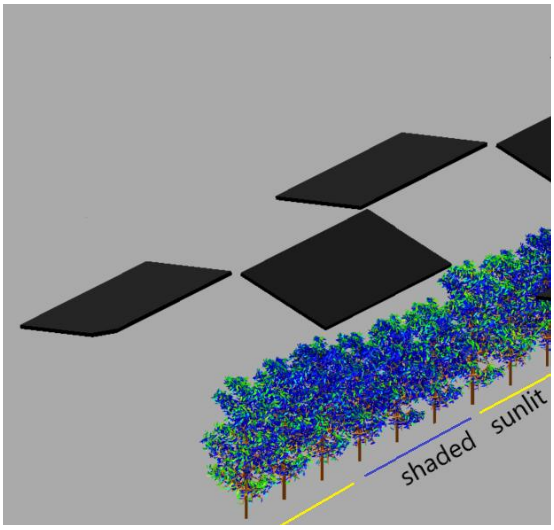

Figure 8: Light distribution for a checkerboard configuration, showing a division in sunlit and shaded areas.

5.3 Semi-transparent modules

The case study of the checkerboard configuration shows clearly the impact of the module dimensions on the solar radiation distribution. One solution to overcome this issue is the use of semi-transparent modules, where standard 6" cells are equally spaced over the module area.

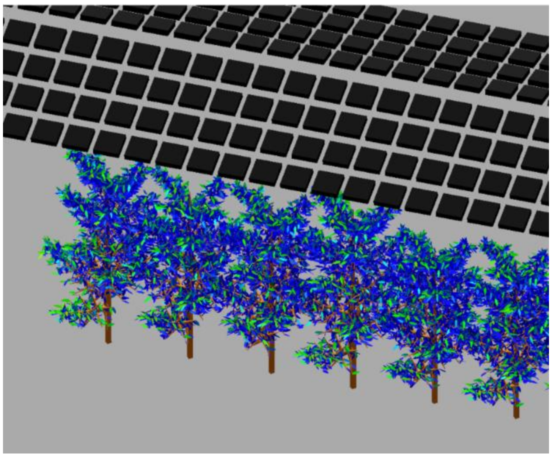

Figure 9: Homogeneous light distribution below semi-transparent modules.

Table 1: Economic analysis

	Opaque landscape	Opaque checkerboard	Semi transparent	Without PV
GCR	60	30	36	0
Energy yield (kWh/tree)	245.62	121.85	146.23	0
Pears per tree	60	79	82	100
Average pear weight (g)	127.50	144.50	149.60	170
Annual revenue: energy yield (€/tree)	22.10	10.97	13.16	0
Annual revenue: agricultural yield (€/tree)	4.59	5.77	7.19	10.2
Total revenue (€/tree)	26.69	16.74	20.35	10.2
Remarks	Unbalanced agrovoltaic system	Heterogenous pear growth: not possible to harvest field in one go; improved quality effects	Homogenous pear growth, improved quality aspects	No improved quality effects (chance of hail and sunburn damage)

A symmetrical cell configuration in the longitudinal direction has been chosen to be sure of the solar radiation homogeneity within the orchard. Based on the previous GCR (and economic considerations explained in section 5.4), a 36-cell (9x4) module with 40% transparency is selected, as shown in Figure 9. Although the GCR is higher in comparison with the checkerboard case, the relative reduction in pears is only 18% and their weight is reduced with only 12%. This is the result of the transparency level and the subsequent improved diffuse light transmission. Semi-transparent modules thus offer the capability to increase the GCR of agrovoltaic systems while the reduction in solar radiation is limited.

Different semi-transparent cell configurations with the same module transparency are simulated. Provided that the cell rows or cell columns are evenly distributed over the module, there is no noticeable difference in intercepted solar amount and distribution. This can partly described by the small cell size in comparison with the planting distance, the module's relative height of 2.2 m and the sun's daily movement across the sky.

5.4 Economic results

The on-site cooling results in a self-consumption rate of 75%. The injection price is set at € 0.03/kWh while the purchased electricity price is € 0.12/kWh. The selling price of the pears is taken at € 0.6/kg.

Both energy and pear revenues from the simulated cases are expressed in relative terms per pear tree in Table 1. This table clearly shows that agrovoltaic systems can increase and diversify farmer revenues. The largest earnings are found for the opaque landscape configuration, which optimizes the energy yield but does not sustain the biomass yield. This indicates the need for a good legislation, for example with a limitation on the maximum GCR or a limitation on relative crop losses.

The second largest revenues are obtained for the semi-transparent module case. Although there is a reduction of 18% in agricultural yield simulated, the modules strongly reduce the risk of hail and sunburn damage.

The integration of the positive quality aspects are allow this case to be considered as a balanced agrovoltaic system.

Note that the annual revenues of the generated electricity only make sense when the levelized cost of electricity (LCOE) of the agrovoltaic system is lower than the average electricity returns (< €0.09/kWh) or when the installation is fully recouped. Considering a Weighted Average Cost of Capital of 6%, this condition is only met for an initial investment lower than €1/Wp (over a period of 20 years). This highlights also the economical limit of the transparency of the semi-transparent modules, where the cost of the PV construction becomes too high in comparison with the PV surface that generates the electricity (savings).

6 PRACTICAL INSTALLATION

A proof of concept has been built in August 2020 based on the techno-economic optimum calculated using the modelling tool discussed in this work. Figure 10 shows the installation of the semi-transparent modules over the pear trees at Bierbeek. This proof of concept will be used in the future to better investigate the PV energy yield, impact of shade on the number of fruits, fruit weight and fruit quality (refining the relations in Figures 5 and 6).

Figure 10: Photograph taken during the installation phase of the agrovoltaic system at Bierbeek.

7 SUMMARY

Combining orchard crops with PV modules shows several benefits in the design due to the row-based crop lay-out and manual farming practices. The system configuration stability, thanks to the long orchard lifetimes and regular placement of fruit trees enables lower-cost mounting structures to be used and improves the financial business case of agrovoltaics in Belgium. Based on a case study in Bierbeek, Belgium, steps are shown to establish a techno-economic optimization, where priority is given to a sustained biomass yield, with an increased biomass quality in line with best agrovoltaic practices.

In order to quantify the impact on the light distribution, biomass yield and energy yield, a novel 3D agrovoltaic modelling tool based on the OpenAlea framework has been developed. It is important to not evaluate annual average results, in contrast, many fruit crops have a critical flowering period that determine the number of fruits.

A comparison with different ground coverage ratios and transparency levels of PV modules is applied. The simulations show that the light interception mainly depends on the GCR. Additionally, the light distribution, which is important for a uniform biomass growth, depends on the module's dimensions. Semi-transparent modules satisfy both requirements, as their transparency result in a homogeneous light distribution while the diffuse light transmission is improved. The transparency level of the modules is the main design parameter, with limited impact of the cell configuration, on condition that the cells are evenly distributed and the modules are placed >2 m above the trees.

The annual revenues show that agrovoltaics systems can increase and diversify the farmers' income, while the protection against hail and sunburn damage is improved.

An evaluation agrovoltaic set-up, based on the simulation results was built in August 2020 at Bierbeek, as one of four such set-ups financed by the TETRA project Agrivoltaics. This set-up is expected to provide important feedback on the feasibility and technical modelling assumptions used.

Agrovoltaic installations can be used to further decarbonize the agricultural and residential sector, while giving at same time new market opportunity for PV installers and developers.

ACKNOWLEDGMENT

This work is the result of the research project funded by VLAIO (Flemish Agency for Innovation and Entrepreneurship), project HBC.2019.2051.

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