The potential of agrivoltaic systems in the conditions of southern regions of Russian Federation

Nikita Kostik¹∗, Alexander Bobyl², Vasiliy Rud², and Islam Salamov³

¹Saint-Petersburg Electrotechnical University “LETI”, Saint-Petersburg, 197376, Russian Federation; ²Ioffe Institute, Saint-Petersburg, 194021, Russian Federation; ³Millionshchikov Grozny State Oil Technical University, Grozny, 364051, Russian Federation

Abstract. The aim of this research is to analyze the potential of agrivoltaic systems (AV) on the territory of Russian Federation. Two configurations of AV systems with 3.2 m and 6.4 m spacing between photovoltaic (PV) arrays were investigated and on the 4 m distance above the crop field. The simulation was performed on the 1 ha of sugar beetroot/lettuce crop field as the most suitable vegetables for shading conditions. The simulation was performed in the conditions of Krasnodar region with average annual solar insolation at 4.20 kWh/m². Net Present Cost of the agrivoltaic system with minimal 3.2m spacing between the arrays is 558277 $US and cost of energy of this configuration is 0.75$US/kWh. Net Present Cost of the agrivoltaic system with 6.4 m spacing between the arrays is 424216$US and Cost of energy is 0.723$US/kWh. Assuming the reduction of sunlight by 30% from 3.2m spacing and by 10%-20% from 6.4 spacing, expected yield of crops is supposed to be 70%-80% of normal yield. Using agrivoltaics for combined use of land allows increasing the productivity of agricultural land by 45%-70% according to Land Equivalent Ratio. With creation comfortable conditions of agrivoltaic development, such systems can have huge impact on the rural off-grid electrification, creating autonomous renewable source of energy.

1 Introduction

Renewable energy systems have the potential to provide the most sustainable and cost-effective power supply, as highlighted in research by L. Ding [1]. Among all renewable energies, solar power is the most abundant and available source [2]. Solar power is also becoming more affordable. The cost of solar panels has fallen by 10% per year for the past thirty years, while production has risen by 30% per year. If costs continue to be reduced based

∗ Corresponding author: aspirin105@gmail.com
on this historic rate, solar energy will be less expensive than coal by 2020[3]. The impact of wide-spread solar installations is an area of increasing interest [4].

To satisfy the energy and food needs of constantly increasing population, modern solution is required. Since we need both fuel to generate energy and food, any land-use optimization must take into account for both types of “generation” at the same time. There are two options for producing both fuel and food using available land resources:

1. Dividing the available land into two parts: one is intended for the production of food, and the other is for the production of fuel. This is current dominant production sharing scheme [5].

2. Consolidation of fuel and food production in the same area. This solution is proposed on the basis of combining solar cells and food crops, as already proposed in the work of Goetzberger [6].

2 Methods

2.1 The crop component

To satisfy energy demand PV solar systems require large spaces for panel installation. Large-scale solar installation may affect the area around the site. The shading from the PV arrays can influence climatology, but the investigations demonstrate contradicting results: PV arrays can create the effect of “heat islands” – : 276–277 K increase in air temperature over solar panels compared to desert conditions at night [7], 273,25–273,65 K decrease in air temperature, 274–275,65 K increase in regional and global temperatures in urban area [8] and a 278,35 K increase in air temperature under solar panels [9].

The possibility of combining the crop fields with PV solar panels were investigated in the works of [10], where the productivity of the vegetation in the conditions of light reduction from PV arrays was investigated. In the research two models were investigated: half density shading of the crops and full density shading of the crops. It was found that wheat crops can compensate the lack of sun by increased dynamics of leaf expansion. As results, a 57% reduction in light availability from shading results in only a 19% reduction in wheat yield. The model predicts that the light efficiency of wheat crop is increased under the shade of by compensating mechanisms of the plant. [11]

It was mentioned that the crops with less root density and high shading tolerance are preferable. [12] In other work, [13] Marrou investigated the effect from air temperature and vapor pressure deficit at crop level are reduced by shading. Authors investigated different density of shading as well as different types of crops: cucumbers, lettuce and wheat. As a result, temperature of the crops under the shading of the PV arrays differs from normal conditions.

In the same work [11] authors, demonstrate how utilization of the agrivoltaics can increase land productivity. From economic point of view, Land Equivalent Ratio (LER) [14,15] is indicator of the productivity of the land used to assess the value of mixed cropping systems and allow comparing the productivity of mixtures of crops on the same land area versus monocultures [16].

2.2 Location component

Northern Caucasus and Krasnodar region are most suitable regions for possible location of agrivoltaic system. Both regions have high solar activity and have available agricultural fields. Krasnodar region is one of the leaders of agriculture production in Russian Federation. Krasnodar region average winter solar insolation in Krasnodar region is 1,95 kWh/m² and average summer insolation is 6,20 kWh/m², annual solar insolation is 4,20 kWh/m². The average January temperature is 270 ...268 K on the plains, 265 K in the mountains and from 273 to 279 K on the Black Sea coast. The average July temperature is 286 K in the mountains
and 295 ... 297 K on the Black Sea coast. Since the beginning of June, the air temperature practically does not drop below 293 K

Fig. 1. Northern Caucasus regions map

The peak of the heat is in August, at this time it is usually 301 K and above [17]. The average annual precipitation is 400-600 mm in the plains and up to 3242 mm in the mountains. Favorable weather conditions and fertile soils allows growing various types of plants. Agriculture of the Krasnodar region specializes mainly in the cultivation of crop products. The share of crop production in the total value of manufactured products in the region in 2015 was 72.7% (242.4 billion rubles), the share of livestock - 27.3% (91.1 billion rubles). Krasnodar region ranks 1st in the Russian Federation for the production of wheat, corn, sunflower, rice, sugar beet, beans. In addition, the region is among the first to harvest barley, soybeans, vegetables. The structure of the cultivated areas of the Krasnodar Territory. In the structure of the sown areas of the region, the largest share is occupied by the cultivation of wheat (40.1% of all areas), corn for grain (16.9%), sunflower (11.9%), barley (4.8%), soybeans (4.5%), sugar beet (4.2%), rice (3.6%). [18]

2.3 The solar panels component

Investigation the potential of the agrivoltaics, various arrays placement were studied. Photovoltaic modules Hevel HVL-380/HJT (1996x1002x30) were used for the simulation. To minimize the effects from shading we investigated stilt mounted configuration. First stilt configuration is placed 4 m above the ground and has 3.2m spacing between the rows of PV arrays [19]. Stilt placement allows more sunlight to penetrate the crop fields, minimizing the shading from the PV arrays during the day. Second stilt configuration has half of the PV strips removed, making the distance between the PV elements 6.4m. Less PV elements in the array letting through an average of 70% of incident radiation available to the crop, while on the full density of the PV elements the incident radiation available to the crop is about 50%.

Fig. 2. Configuration of agrivoltaic system mounted on stilts.
3 Results and discussion

On the 1 ha simulated field we have 30 columns and 47 rows with 3.2 m spacing between the PV modules and 16 columns and 47 rows with 6.4 m spacing. Using Hevel HVL-380/HJT modules with maximum output power of 595.5 kW from 1 ha with 3.2 m spacing between modules and 387.1 kW for 6.4 m spacing between PV modules. Both of the systems have 36˚ inclination towards south, which is optimal annual position for maximum efficiency of PV systems. Less PV elements in the array letting through an average of 70% of incident radiation available to the crop.

![Satellite photograph of the location of 6.4 m spacing agrivoltaic systems (a) and a fragment of the location of 6.4 m spacing agrivoltaic systems on a larger scale (b)](image-url)

Fig. 3. Satellite photograph of the location of 6.4 m spacing agrivoltaic systems (a) and a fragment of the location of 6.4 m spacing agrivoltaic systems on a larger scale (b)
Figure 3 shows possible options for the placement of agrivoltaic systems in the Shelkovsky district of the Chechen Republic. Simulation was performed in the condition of Novosherbinovskaya farming settlement (46.28N, 38.4E) of Krasnodar region and the Shelkovsky district of the Chechen Republic (43.31N, 45.57E). It was decided to simulate the performance of the agrivoltaic system on the fields of sugar beetroot or lettuce, as most preferable plants. Beetroots and lettuce have proven to be shade-tolerant, adaptive to the changing conditions vegetables that are most suitable for implementing in the agrivoltaic systems [13]. Height of crops is a key parameter for selection of crops for agrivoltaic system because tall-growing crops may create shade on PV-module and thus reduce the PV-based electricity generation. Therefore, crops with low height (preferably shorter than 50cm) and which tolerates certain degree of shade and require less amount of water are most suitable for AVS. Available for cropping purpose area changes as per design of the installation – ground mounted PV systems create more shading and take more space for installment, which make ground configuration of PV agrivoltaics more preferable for pastures and animal farming.

Table 1 – Annual performance of the agrivoltaic system with 3,2m spacing between the PV arrays.

| Month       | Energy Sold, kW | Energy charge, $US |
|-------------|-----------------|--------------------|
| January     | 32,711          | $1,308.43          |
| February    | 38,686          | $1,547.45          |
| March       | 49,387          | $1,975.47          |
| April       | 55,980          | $2,339.21          |
| May         | 69,166          | $2,766.63          |
| June        | 67,921          | $2,716.83          |
| July        | 72,877          | $2,915.08          |
| August      | 67,514          | $2,700.56          |
| September   | 58,408          | $2,336.32          |
| October     | 46,501          | $1,860.04          |
| November    | 30,509          | $1,220.37          |
| December    | 27,340          | $1,093.60          |
| Annual      | 617,000         | $24,679.99         |

As a result, agrivoltaic system with 3,2 m spacing between PV arrays, generated 721216 kWh per year. To simulate possible profit of the agrivoltaics system we assumed the sell price of the energy to be at 0.04$/kWh. Based on the price of the 300 W PV module at 254$US and additional 1250$US for installation of system, Net Present Cost of the agrivoltaic system with minimal 3.2 m spacing between the arrays is 558277 $US over 25 year lifetime of the system. With estimated selling price of electricity at 0,04$US/kWh the breakeven point of the system is going to be after 23 years. Cost of Energy in that case is 0.7$US/kWh.

Table 2 – Annual performance of the agrivoltaic system with 6,4m spacing between the PV arrays.

| Month       | Energy Sold, kW | Energy charge, $US |
|-------------|-----------------|--------------------|
| January     | 23,314          | $932.56            |
| February    | 28,264          | $1,130.58          |
| March       | 35,967          | $1,438.69          |
| April       | 39,617          | $1,584.69          |
| May         | 50,466          | $2,018.62          |
| June        | 48,920          | $1,956.80          |
| July        | 53,337          | $2,133.49          |
| August      | 50,516          | $2,020.65          |
| September   | 44,275          | $1,770.99          |
| October     | 32,588          | $1,303.50          |
| November    | 22,213          | $888.50            |
| December    | 18,536          | $741.44            |
| Annual      | 448,013         | $17,920.52         |
High cost of investment is a major hindrance for its adoption in farmers’ field. Therefore, policy supports and guidelines are necessary for establishment of agrivoltaic system in farmers’ field. For the configuration with 6.4 m spacing between the rows less number of PV elements caused huge decrease in the energy generation. In the simulated model only 471593 kWh was generated during the year. Net Present Cost of the agrivoltaic system with 6.4 m spacing between the arrays is 424216 $US over 25 year lifetime of the system. Cost of Energy in that case is 0.723 $US/kWh. Less PV elements allows decreasing overall cost of the system, but relatively low selling price of the energy to the grid still limits the payback period.

With Land Equivalent Ratio (LER) it is possible to calculate estimated productivity of combined land use (1). LER is developed to estimate the productivity of land when a mixture of crops is used [20,21] was proposed by Dupraz et al. [22] as indicator of land productivity under agrivoltaic systems.

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LER = \left( \frac{Y_{\text{crop AV}}}{Y_{\text{monocrop}}} \right) + \left( \frac{Y_{\text{electricity AV}}}{Y_{\text{electricityPV}}} \right)
\]

Where \(Y_{\text{crop AV}}\) is the total dry mater or grain yield (kg m\(^{-2}\)) of agrivoltaic system, \(Y_{\text{monocrop}}\) is yield of conventional agricultural field with full sunlight availability (kg m\(^{-2}\)). Similarly, \(Y_{\text{electricity AV}}\) and \(Y_{\text{electricityPV}}\) (kg m\(^{-2}\)) are the electrical production obtained respectively under an Agrovoltaic system and a reference PV plant. In case of minimal spacing of 3.2 m between the PV arrays, electricity productivity is assumed to be 1. Half density and spacing of 6.4 m reduced the number of PV arrays and the electricity productivity is assumed to be 0.65.

Based on the investigations of PV shading on the agricultural land, we assumed that in the case of 3.2m spacing between PV arrays, the amount of sunlight is reduced by almost 40% compared to the land without agrivoltaic systems. Studies also demonstrate the shading affecting the microclimate under the PV arrays and plant development rates. It was found that shading slows the speed of the lettuce plants development by 2-3 weeks in phases after the planting. In our case we assumed the plant relative yield to be 0.7 for the 3.2m spacing. Bigger 6.4m spacing reduces the shading effect, allowing up to 70% of incident radiation to reach the crops underneath the PV arrays. For the 6,4m spacing we assumed the relative plant yield to be 0.9. It should be mentioned that these values are assumption and based on the performed experiments, conditions and may with different features of plants.

Table 3 – Simulation of Lane Equivalent Ratio of agrivoltaics systems.

|                      | Solar panel generation | electricity | Crop relative yield | Total LER |
|----------------------|------------------------|-------------|---------------------|-----------|
| **Monosystem**       | 1                      | 1           |                     | 1.0       |
| Agrivoltaic 3,2m spacing | 0.65                  | 0.8         | 0.7                 | 1.45      |
| Agrivoltaic 6,4m spacing | 0.65                  | 0.8         | 0.7                 | 1.45      |

However, if we take into account the agricultural aspect of the additional selling price of the crops. According to expert and analytical center for agribusiness "AB-Center"[18], it is possible to get 1000-1100$US from 1 ha of sugar beetroot and 4285 – 4500$US from 1 ha of lettuce. This demonstrates the possibility of drastically increasing the profits from agricultural land with only slight reduction of crop yields.

Agrivoltaic systems may bring huge opportunity for the distant rural farming settlements, creating autonomous off-grid systems that can supply the production needs and satisfy the demands of nearest settlements.

Other important effect from agrivoltaic systems, that it can create the comfortable conditions for vegetation via shading from PV arrays. Improvement microclimate for crop cultivation, reduced soil erosion from wind and decreasing ambient temperature around the PV arrays during the day as well as the ground cooling speed during the night.

However it should be mentioned that some policy interventions may be required to establish agrivoltaic system in farmers field. It may be loaning through banking sector for
installment of agrivoltaic due to high initial cost of the system. Capital investment on
agrivoltaic system is quite high and therefore subsidy may be introduced to promote
systems[23]. As well as introduction of special tariffs, to create comfortable environment for
selling produced energy.

4 Conclusions

The study demonstrates possibilities of combined use of agricultural lands – crop fields and
electricity generation via photovoltaic modules.

1. Agrivoltaic system on the stilts with different configuration of PV arrays spacing were
investigated. With optimal inclination towards south at 36° it is possible to generate 595.5
kW and 387.1 kW for 3.2m and 6.4 spacing between arrays respectively.

2. Assuming selling price of energy at 0.04US/kWh, agrivoltaic system with 3.2m
spacing can sell 617,000 kW at total price $US 24,679.99 each year. 448,013 kW of
electricity at the total price of $US 17,920.52 per year can be sold, using the agrivoltaic
system with 6.4m spacing.

3. Agrivoltaic systems can increase overall land productivity from 50% to 70% by
combined use of agricultural lands.

4. Depending on type of the crops, PV shading effect can positively affect the
microclimate for the vegetation – reducing the erosion of soils, increasing the moisture and
ambient temperature.

5. Investigated systems can create comfortable conditions for rural settlements and
farming in distant regions by representing off-grid source of energy. Future work is needed
to verify the results of this simulation so that agrivoltaic systems can be implemented in the
rural areas and villages, which can be electrified apart from the added advantage of growth
in revenue.

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