A promising line of development of solar energy

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Abstract. By analyzing the electricity generation and the capabilities of modern photovoltaic power stations (PPS), we assessed the expenditures connected with the transition to solar power production. We also examine the issue related to improving the efficiency of PPS through the use of Stokes and anti-Stokes coatings. Analytical expressions are obtained for the voltage value of the photovoltaic cell (PC) at a different distance from the beginning of the cell as well as dependences of the working voltage on the source length.

1. Introduction
The world development tendencies in power generation are proceeding toward renewable sources, such as hydro power resources (rivers, and tides), wind, bioresources, and solar energy. In essence, the first resources, except for tides, are derived from the solar energy absorbed on Earth. The main disadvantages of solar energy are its low power obtained from the unit of area, and its dependence on season, time of day and atmospheric transparency, i.e. weather. The progression of solar power was retarded by such factors as the high cost of solar photovoltaic cells as well as by their low efficiency. As far as the cost of solar cells is concerned, with the advances in technologies of obtaining silicon with a purity sufficient for the manufacture of solar cells, its prime cost has decreased from $450 per kg to $15–20 for the last decade [1].

Such a result is provided by a direct obtaining of so-called multicrystalline silicon (multisilicon) by the method of direct recovery from naturally pure quartzites [2].

While at earlier dates the efficiency of PC did not exceed 10%, recent years saw the advent of appropriate methods of solar energy conversion by decomposing it into separate spectral components in order to increase efficiency to 40% [3]. On the other hand, there are some avenues for improving the performance of PC, in particular by improving PC efficiency through the use of luminophores.

Such advances in technologies of using and generating electricity by means of PC hold promise as regards the transfer of current electric power generation largely to solar power.

It is suggested that the difficulties associated with the irregularity of energy supply should be coped with by the following methods. For the Russian Federation that has 10 time zones, about 10 PPS should be constructed. An excellent place for siting PPS to supply energy to the eastern part of Russia appears to be the Crimean Peninsula. These PPS, combined into the unified energy system, would supply electricity to regions hitherto lacking it. Extra electric energy must be accumulated in enterprises to obtain methanol to be stored and subsequently used in thermal electric plants (TEP) and in transport [4]. By developing the power generation industry along this direction, it is possible to solve several problems simultaneously: use of inexhaustible renewable resources, a minimization of thermal pollution of the planet from TEP and nuclear electric plants (NEP), a decrease in carbon dioxide emissions, and
switchover of transport to methanol. We have also considered the issue of how to decrease the voltage at the PPS output in the case of a large longitudinal size.

2. Materials and Methods

Let us consider the requirements which arise in the case of switchover to solar power. We shall start from the conditions which decrease as much as possible the PPS end efficiency, namely the energy is accumulated to methanol according to the scheme: decomposition of water into oxygen and hydrogen, and bonding of hydrogen with carbon dioxide to obtain methanol [5]. With today’s technologies, the losses make up about 50%.

As is apparent from data reported in [6], the Sun in mid-latitudes provides 3.5–4.5 kW h per day for the area of one square meter. Considering what has been said above concerning the losses connected with the accumulation and transfer of electric energy from PPS to the user, it is assumed that 1 m² of PC generates 1 kW h per day, which corresponds to the power of 40 W. Data in Table 1 [7] permit us to estimate the area of PC for supplying electric energy to the world and Russia. For the world, this area is about 150 000 km², and for Russia it is about 6000 km², i.e. the territory 77x77 km² in size!

| In the world | GW - | Share in % | In Russia | Share in % of world generation | Share in % in RF |
|-------------|------|------------|-----------|-------------------------------|-----------------|
| Installed power | 6039.81 | 100 | 235.4 | 3.9 | |
| TEP (coal, natural gas, oil) | 3818.82 | 63 | 160.3 | 4.2 | 68.1 |
| NPS | 376.15 | 6.2 | 27.15 | 7.2 | 11.5 |
| HEP | 1038.26 | 17.2 | 47.86 | 4.6 | 20.34 |
| Pumped storage EP | 143.33 | 2.4 | - | - | - |
| Renewable energy sources (without HEP) | 663.2533 | 10.9 | - | - | - |
| Geothermal EP | 11.43 | 0.18 | 0.08 | 0.7 | 0.03 |
| Wind plants | 374.20 | 6.2 | 0.011 | 0.003 | 0.005 |
| Solar stations | 174.20 | 2.9 | 0.060 | 0.03 | 0.03 |
| Biomass and wastes | 100.01 | 1.6 | - | - | - |
| Power plants using the energy of waves and oceanic currents | 2.94 | 0.05 | 0.002 | 0.07 | - |
| Electric energy consumption, TW h | 20715.76 | 100 | 1049.9 | 5.1 | 100 |

The total amount of silicon which is necessary for the implementation of such a project is about 7.5 million tons provided that 50 g of silicon per 1 m² are used for PC generation. For Russia, the need for silicon will not exceed 300 thousand tons. With the explored reserves of several km³ in Russia, this raw material is more than sufficient for obtaining solar silicon for PC with the cost of $15. Even with today’s prime cost of one square meter of PC equal to $50, the cost of PPC for supplying the required amount of electricity to the entire Earth will not exceed $0.3 billion, or 18 billion of rubles, which constitutes the actual expenditures for the budget when this amount is distributed during 10–15 years.

At this point it should be noted that the USA and PRC have a substantially larger number of areas located south of latitude 52° (i.e. the latitude, to the north of which a large part of the territory of the Russian Federation lies); therefore, the implementation of the solar energy project will bring a high economic effectiveness for them.

Buryatia, Irkutsk oblast and Mongolia may well become the candidate regions for the development of solar power. The need to deploy such a pilot project in these regions is dictated by the fact that the
Government of Mongolia is planning to construct (with the purpose of providing the country with renewable sources of energy) a cascade of HEP on the Selenga river. This water artery was navigable prior to the early 1960s accounts for about half the inflow of water to Lake Baikal [8]. The power of the planned HEP is about 245 MW [9]. To supplant such a power with solar energy requires the construction of PPS with the area of PC measuring about 6 km$^2$, with the cost of $30 million, or 18 billion rubles. The implementation of this project with the aid of Russia would be for the benefit of Russia and mankind, because it would be beneficial for the preservation of Lake Baikal that concentrates more than 20% of the world reserves of surface drinking water. On the other hand, the development of solar energy in Buryatia and Irkutsk oblast would help to minimize the substantial backwardness of Russia as regards the utilization of the latest achievements of science and technology in the domain of energy saving. For instance, Bratsk HEP has the installed power of 4.5 GW and the area of its reservoir 5470 km$^2$, which compares with the area of PCs (6000 km$^2$) necessary for the replacement of all electric energy generation facilities in Russia. It must be borne in mind, however, that in the event of using the controlled and Sun-oriented PC in the morning and evening hours, the area needed to locate PC depends greatly on the angle of elevation of the Sun. Its size will increase in inverse proportion to the tangent of the angle of elevation squared, i.e. with the angle of elevation of 30 degrees, the area will increase three times, and when the angel of elevation is twice as small, 14 times.

The main expenditures of energy in Russia correspond to the creation of comfortable habitat conditions. In the setting of East Siberia, energy saving is a particularly challenging issue. In spite of the large reserves of renewable energy sources (hydroelectric power generation facilities, wastes of forest harvesting and processing), the tapping of solar energy and wind energy to supply electricity to territorially distant communal facilities is of particular current importance.

Nowadays, it is strongly suggested that at the present time, it is strongly suggested that instead of the expected warming on the globe, one should expect a cooling period of about 40-60 years, in analogy with the Maunder minimum of sunspots that occurred in the second half of the 17th century and associated with 400 summer variations in the solar constant [10-12,17] after the year 2030.

In view of the difficulties with storage of hydrogen, the prospects for hydrogen-based generation of energy are very obscure [13]. Therefore, the suggested concept of using methanol as the accumulator of energy reserves has considerable promise [4, 5].

The existence of major HEP and TEP in the Irkutsk region makes it possible to avoid (when implementing the pilot project) difficulties in electricity supply to the population and industries. Furthermore, TEP provide powerful sources of carbon dioxide for the manufacture of methanol [4, 5]. This opens up the scope for achieving two promising goals at once: to decrease carbon dioxide emissions in order to minimize the greenhouse effect, and to accumulate extra solar energy and other kinds of energy in methanol for its subsequent utilization to generate electric energy as well as for transport purposes.

3. Results
In [14], we explored the possibility of improving efficiency of semiconductor photovoltaic cells (PC) for solar energy conversion by using Stokes and anti-Stokes luminescent covers (ALC) [14]. The requirements were formulated for ALC used to improve PC efficiency. Spectroscopic characteristics of luminophores meeting the requirements were systematized.

The software program was developed for computing the ratio of efficiency of PC with ALC to efficiency of a usual silicon PC (relative efficiency). The actual energy distribution in the ALC radiation spectrum was taken into account as well as in the absorption spectrum of ALC and in the absorption spectrum of silicon. The ALC excitation spectrum was modeled in the form of a rectangle, with the mean intensity value within the spectrum. The differences of the reflection processes of PC with ALC and a conventional PC were neglected.

The software program thus developed took into consideration the losses caused by the passage of radiation through PC without being absorbed therein, including when $\lambda > \lambda_0$, where $\lambda_0$ is the boundary of the main absorption band (in the event of using ALC, these losses are decreased), as well as the losses
caused by recombination processes on the front and back surface and in the PC volume (spectral collection coefficient). It is this kind of losses that appears to be the main kind of losses that is decreased when using ALC in the case where the main excitation spectral region of ALC is close to \( \lambda_0 \).

Calculations were done preliminarily when using a model spectral dependence of the of the collection coefficient of a silicon PC with the luminophore coating 0.15 in thickness by using large values of the parameter \( L_{\text{rad}} \) (\( L_{\text{rad}} \) – path traversed by solar radiation in the semiconductor). Results of calculations indicate a fundamental possibility of improving PC efficiency by converting the radiation with ALC; however, the value of the effect is small. In using the characteristics to model the use of different ALC, an improvement in efficiency was for YOCI luminophore: \( E_\text{r} \), Yb – 0.8%, and for YbOCl: \( E_\text{r} \) – 1.1 %. In the case of luminophore \( Y(0.74)Yb(0.25)Er(0.01)OCl \), the increase in efficiency approached 2%.

It is also of interest to mention the following. Since the value of the spectral collection coefficient of the semiconductor PC decreases drastically in the shortwave spectral region [15], an improvement in relative PC efficiency can also be achieved through the use of coatings on the basis of conventional (not anti-Stokes) luminophores converting shortwave ultraviolet to visible radiation.

We want also to notice one important characteristic of the source of electric energy with a large spatial size, such as the solar cell. The load in the form of a resistor, for example (we denote its resistance as \( R_2 \)) is connected to the source usually locally, that is, to the poles of one of many PC. In this case, the current flowing on the load resistance passes through many PC along the plane of the p-n transition. The operation of such a circuit of many PC and load is similar to the operation of power lines with distributed parameters [16].

Let us consider the characteristics of the operation of the electric energy source having regard to its length along the axis \( x \). In this case, we use the following notation: \( r_0 \) – active resistance of the source along the p-n transition per unit of line length, and \( g_0 \) – conductivity of the source across the p-n transition per unit of line length. Then the resistance of an infinitely small segment of the line length \( dx \) will be \( dr = r_0 dx \), and conductivity of this segment \( dg = g_0 dx \), \( l \) – length of the source along the direction \( x \).

The main difference from the line with distributed parameters lies in the fact that the extended source uses charging currents instead of leakage currents.

Let us consider a dependence of the voltage between the upper and lower surfaces of PC \( U \) and current \( I \) on the distances \( x \) from the end of the line (of an extended source). In this case, the voltage and current at the end of the line, \( U_2 \) and \( I_2 \), are considered known.

A voltage drop in the element \( dx \), as in a usual line with distributed parameters [16], becomes
\[
dU = l dr = l r_0 dx. \tag{1}\]
A change in the strength of current due to the passage of charging current (unlike the leakage current in a usual line) has the form
\[
dI = -(E-U) dg = -(E-U) g_0 dx. \tag{2}\]
Here \( E \) – EMF of the source – voltage \( U \) with the open switch prior to load (at idle). From equations (1) and (2) we have
\[
\frac{dU}{dx} = I r_0, \tag{3}
\]
\[
\frac{dI}{dx} = -(E-U) g_0. \tag{4}\]
We see that the difference from the usual line [16] lies in equation (4).

By differentiating the two sides of equation (3) and replacing \( \frac{dI}{dx} \) from equation (4), we obtain
\[
\frac{d^2U}{dx^2} = -(E-U) g_0 \beta_0. \tag{5}\]
This inhomogeneous second-order differentiation equation describes a dependence of the voltage \( U \) on the distance \( x \). Its general solution has the form
\[
U = E - (A_1 e^{\beta x} + A_2 e^{-\beta x}), \tag{6}\]
where \( \beta = \sqrt{l r_0 g_0} \) is the analog of the attenuation factor of a long line.

From (3) we have
where \( r_c = \sqrt{\frac{r_0}{\theta}} \) is characteristic resistance.

Upon substituting (16) into (6, 7), we obtain a dependence of the voltage and strength of current in the source on the distance x

\[
U = E - \left[ \frac{1}{2} (E - U_2 - r_c I_2) e^{\beta x} + \frac{1}{2} (E - U_2 + r_c I_2) e^{-\beta x} \right],
\]

\[
I = -\frac{1}{2} (E - U_2 - r_c I_2) \frac{1}{r_c} e^{\beta x} + \frac{1}{2} (E - U_2 + r_c I_2) \frac{1}{r_c} e^{-\beta x}.
\]

The voltage and the current at the edge of the source on the other side of the load is obtained by substituting \( x = l \) into these dependencies

\[
U_1 = E - \left[ \frac{1}{2} (E - U_2 - r_c I_2) e^{\beta l} + \frac{1}{2} (E - U_2 + r_c I_2) e^{-\beta l} \right],
\]

\[
I_1 = -\frac{1}{2} (E - U_2 - r_c I_2) \frac{1}{r_c} e^{\beta l} + \frac{1}{2} (E - U_2 + r_c I_2) \frac{1}{r_c} e^{-\beta l}.
\]

The load resistance \( R_2 \), the voltage \( U_2 \) and the current \( I_2 \) are interrelated by Ohm’s law, that is,

\[
R_2 = \frac{U_2}{I_2}.
\]

In the mode of matched load (when \( R_2 = r_c \)), from (9, 10) we have

\[
U = E (1 - ch \beta x) + U_2 e^{\beta x},
\]

\[
I = -\frac{E}{r_c} sh \beta x + I_2 e^{\beta x}.
\]

As in the usual line with distributed parameters, a change in the voltage along the source in the extended source under consideration is caused by a voltage drop on resistance of the source along the p-n transition at the passage of current. It may therefore be assumed that when \( x = l \) we have \( U_1 = E \). From (11) we then have

\[
U_2 = E \cdot f_i,
\]

where

\[
f_i = \frac{ch \beta l}{ch \beta l + \frac{r_c}{R_2} sh \beta l}.
\]

Upon substituting (16) into (9), we obtain

\[
U = E \left[ 1 - \left\{ \frac{1}{2} \left[ 1 - f_i - \frac{r_c}{R_2} f_i \right] e^{\beta x} + \frac{1}{2} \left[ 1 - f_i - \frac{r_c}{R_2} f_i \right] e^{-\beta x} \right\} \right],
\]

In the mode of matched load, from (14) we have

\[
U_2 = E \frac{ch \beta l}{e^{\beta l}} = E \frac{e^{\beta l} + e^{-\beta l}}{2 e^{\beta l}} = \frac{1}{2} E \left( 1 + e^{-\beta l} \right) = \frac{1}{2} E \left( 1 + \frac{1}{e^{2 \beta l}} \right).
\]

Upon substituting (18) into (14), we obtain

\[
U = E \left[ 1 - ch \beta x + \left( \frac{1}{2} + \frac{1}{2 e^{2 \beta l}} \right) e^{\beta x} \right],
\]

\[
I = \frac{1}{r_0} \frac{du}{dx} = E \frac{\beta}{r_0} \left[ \frac{1}{2} + \frac{1}{2 e^{2 \beta l}} \right] e^{\beta x} - sh \beta x.
\]
4. Conclusions
The resulting relations appear to have a general character for extended sources; in particular, they hold true for long chemical sources of current. Of most interest for practical implementation is the expression (19) describing a decrease in “working” voltage $U_2$ as a function of the source length, which is of interest when designing PPS with long PC.

Thus the research presented in this paper has showed that the current technological level of development of science and technology opens up possibilities for a wider use of solar energy in the world and in the Russian Federation.

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