Estimation of solar energy resources for low salinity water desalination in several regions of Russia

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Abstract. This paper focuses on estimation of demanded photovoltaic (PV) array areas and capital expenses to feed a reverse osmosis desalination unit (1 m³/day fresh water production rate). The investigation have been made for different climatic conditions of Russia using regional data on ground water salinity from different sources and empirical dependence of specific energy consumption on salinity and temperature. The most optimal results were obtained for Krasnodar, Volgograd, Crimea Republic and some other southern regions. Combination of salinity, temperature and solar radiation level there makes reverse osmosis coupled with photovoltaics very attractive to solve infrastructure problems in rural areas. Estimation results are represented as maps showing PV array areas and capital expenses for selected regions.

1. Introduction
Fresh water stress is a very important problem for modern world. There are 200 000 km³ of renewable fresh water resources for now and by 2030 only 60% of the global water demand could be met (according to a business as usual scenario) [1]. Desalination of seawater, law salinity and brackish water from ground and underground sources can promote local water resources to solve this problem. Reverse osmosis (RO) is a prospective desalination technology, effective in a large range of desalination plant productivity. It is especially suitable for small local consumers such as farms, households, small facilities in different branches of industry. Advances in RO allowed to decrease energy consumption, for instance, for seawater desalination from 12 to 2 kWh/m³ [2]. Local renewable energy sources can be used for electricity supply of RO in remote locations. Such approach is widely used by different countries in Africa and Asia which are facing fresh water problem [3]. In Europe, the RO coupled with renewable energy sources is used for brackish water recovery [4].

In Russia several southern regions are facing the fresh water shortage problem. All these regions are characterized by high solar energy potential and intensive development of agriculture and require even larger amounts of fresh water than urbanized areas [5]. In steppe regions of Russia a large amount of salt is accumulated in so called vadose zone as a result of evaporation. The closer ground water is located to the surface, the higher the level of mineralization ceteris paribus. When groundwater is shallow (up to 1 m), the accumulation of salt on the surface may occur.
Figure 1. Experimental data [7] and polynomial approximation for specific energy consumption (a) and final water salinity (b) on initial water salinity for the BW30 membrane.

In arid and semi-arid areas, groundwater is often formed with a high salinity level (10–20 g/L) or more \((1 L = 0.001 \text{ m}^3)\) and has a sulfate-chloride or chloride composition. The most troubled regions of Russia in terms of mineralization of groundwater are the Lower Volga region, the Republic of Kalmykia, and others. Kalmykia is a region with large areas subjected to anthropogenic desertification. Groundwater in Kalmykia is mostly characterized by a high mineralization level (1.6–10.0 g/L) with total hardness of 12.5–22 mEq/L, a high content of chlorides, sulfites, sodium and magnesium [6]. Some seaside areas (Crimea, Dagestan (partly), Astrakhan, Krasnodar and Rostov region) are also characterized by high salinity of groundwater (up to several tens of g/L) due to the sea water intrusion in conditions of intensive usage of groundwater.

These regions are characterized by substantial resources of solar energy and by the presence of fresh water consumers (transhumance grazing, irrigation farming), for which a desalination system with independent power supply is valid. Therefore, in this study we have performed a comparative analysis of different desalination system compositions for climatic conditions of southern Russia. Particularly, technical and economical estimations of a photovoltaic system (PV) coupled with a RO desalination system application for local water supply were carried out.

2. Initial data for calculation
Initial data on solar energy were taken from [8]. Salinity data has been collected from [9]. RO specific energy consumption is the most important parameter for PV–RO coupling and depends on initial salinity, permeate flow and temperature. The review data on specific energy consumption for RO desalination is given in table 1 [10]. It is noteworthy that due to a large dispersion of plants ages it was difficult to make a treated water salinity correlation analysis of the data.

So, for further analysis we need to consider small RO plants with productivity of 1–20 m\(^3\)/h operated at pressure conditions of 20 bar. Water temperature influence is neglected due to ground water usage as water source. In [7] performance data for 3 types of membranes are given. One of them (BW30 from Filmtec) is a special membrane for RO brackish water desalination and two of them (NF90 from Filmtec and TFC-4920-S from Fluid Systems) are usually used for
Table 1. Estimated energy consumption of some reverse osmosis plants launched in various years.

| The original water salinity (g/L) | Plant performance (m³/day) | Specific energy consumption (kWh/m³) | Year of commissioning |
|-----------------------------------|----------------------------|-------------------------------------|----------------------|
| 3.50                              | 53.0                       | 0.89                                | 1986                 |
| 3.50                              | 0.50                       | 2.00                                | 2003                 |
| 5.00                              | 0.40                       | 1.86                                | 1982                 |
| 1.60                              | 1.50                       | 1.40                                | 2003                 |
| 5.30                              | 1.10                       | 1.50                                | 2008                 |
| 1.00                              | 5.00                       | 2.30                                | 1999                 |
| 3.36                              | 8.00                       | 2.50                                | 1998                 |
| 5.70                              | 0.55                       | 4.90                                | 1982                 |
| 8.00                              | 40.0                       | 5.50                                | 1990                 |
| 7.00                              | 3.60                       | 2.40                                | 1999                 |
| 6.00                              | 4000                       | 1.72                                | 2000                 |
| 1.53                              | 6000                       | 0.83                                | 2002                 |
| 6.75                              | 25000                      | 1.20                                | 2003                 |
| 1.75                              | 5000                       | 1.55                                | 2010                 |
| 0.60                              | 1200                       | 0.86                                | 2007                 |
| 1.70                              | 5000                       | 0.85                                | 2003                 |
| 1.20                              | 6.00                       | 3.03                                | 2000                 |
| 1.70                              | 0.22–1.27                  | 1.90                                | 2011                 |
| 3.70                              | 3300                       | 1.10                                | 2003                 |

Ultrafiltration. Approximations for specific energy consumption and recovery dependences on initial water salinity were made based on experimental data from [7] in the initial salinity range of 1–21 g/L. Experimental data from [7] describing final salinity and specific energy consumption were approximated via third-degree polynomial function which fits the data best in the range of 0–21 g/L for all types of membranes. The result is presented in figure 1.

Figure 1 shows quite huge specific energy consumption for a relatively high level of salinity (ranging from 10–15 g/L) in case of BW30 application which gives the best final salinity of all membranes presented. Two other membranes give less specific energy consumption but much more final salinity value. Because of high energy consumption and according to [11], two-step and three-step processes (with different combinations of NF90, TFC-4920-S and BW30 as a final step) were used in further calculations due to its lower energy consumption (figure 2).

It is worth mention that such combinations as TFC-4920+NF-90+BW-30 and TFC-4920+BW-30 are the most energy effective, but the first one is characterized by lower output salinity for a large initial salinity range than the second one. Therefore, the specific energy consumption approximation of TFC-4920+NF-90+BW-30 was chosen for further estimations.

Based on this membrane combination, demanded PV array areas and costs were estimated for several regions of Russia. It was assumed that desalination unit operates directly from PVs without battery bank, because the previous research showed the best economic indicators of such a combination [5]. Estimations were made based on data from [8] for selected locations for a month of the highest solar insolation level. Estimations were also made for yearly average insolation data. Locations were chosen based on available ground water salinity data. For each location energy consumption for 1 m³/day desalination in a three-step scheme has been
Figure 2. Specific energy consumption (a) and final salinity dependence on initial water salinity (b) for different membrane module combinations.

estimated using final salinity and specific energy consumption approximations for these three membranes \( W_{\text{cons}} \). It is difficult to use a detailed water consumption profile for the whole year in calculations. So a specific water consumption value \( 1 \text{ m}^3/\text{day} \) is taken for further estimations. Temperature dependences for salinity and energy consumption were not taken into account due to the fact that the ground water temperature is approximately constant throughout the year.

For an average day in \( j \)-th month of the year using data from [8] for a selected location one can obtain a daily average energy production of a PV array \( W_{pj} \) as:

\[
W_{pj} = N_{\text{mod}} S_{\text{mod}} A_j \eta_j \eta_{\text{inv}},
\]

where \( N_{\text{mod}} \)—total amount of PV modules in the array, \( S_{\text{mod}} \)—area of a single PV module of a chosen type, \( A_j \)—daily average solar radiation for \( j \)-th month, \( \eta_j \)—daily average efficiency of PV modules for a typical day of \( j \)-th month, \( \eta_{\text{inv}} \)—averaged PV inverter efficiency (it is taken equal to 0.95).

Average operating temperature of the PV module in \( j \)-th month is calculated by:

\[
T_{\text{mod}j} = T_j + \frac{A_j(N_{\text{oct}} - 20)}{0.8t_{dj}},
\]

where \( T_j \)—average environment temperature, \( N_{\text{oct}} \)—operating temperature of PV cells of the module (under 800 W/m\(^2\) and 20 °C), \( t_{dj} \)—the daylight time for a given month (empiric equation is based on the value of solar radiation flux, not on energy, so to estimate averaged flux it is necessary to take the ratio of averaged energy to averaged daylight time). The coefficient 0.8 comes from the fact that in [12] 800 W/m\(^2\) is used while in [8] all values of solar radiation are given in kWh/m\(^2\)/day.

To calculate average efficiency of the PV module for \( j \)-th month the following empiric equation from [12] was used:

\[
\eta_j = \eta_{\text{STC}}[1 + k_t(T_{\text{mod}j} - 25)],
\]
Table 2. Demanded area ($S_{pv}$) and capital cost ($C_{pv}$) for the PV power unit for RO desalination in selected regions of Russia (based on insolation data [8] for July).

| Name          | Latitude | Longitude | $S_{pv}$ (m²) | $C_{pv}$ (USD) |
|---------------|----------|-----------|---------------|----------------|
| Volgodonsk    | 47.51°   | 42.15°    | 6.67          | 3162           |
| Kotelnikovo   | 47.63°   | 43.15°    | 3.27          | 1581           |
| Taganrog      | 47.22°   | 38.92°    | 3.34          | 1581           |
| Volgograd     | 48.70°   | 44.52°    | 3.21          | 1581           |
| Krasnodar     | 45.37°   | 38.43°    | 2.31          | 1054           |
| Novorossiysk  | 44.72°   | 37.75°    | 11.73         | 5270           |
| Maykop        | 44.60°   | 40.08°    | 5.86          | 2635           |
| Stavropol     | 45.05°   | 43.98°    | 25.36         | 11 594         |
| Mineralnye Vody| 44.21° | 43.13°    | 15.24         | 6851           |
| Nalchik       | 43.48°   | 43.62°    | 14.31         | 6324           |
| Ordzhonikidze | 45.05°   | 35.38°    | 13.83         | 6324           |
| Grozny        | 43.32°   | 45.72°    | 14.31         | 6324           |
| Makhachkala   | 42.97°   | 47.50°    | 3.58          | 1581           |
| Derbent       | 42.05°   | 48.30°    | 11.12         | 5270           |
| Elista        | 46.32°   | 44.27°    | 14.72         | 6851           |
| Djankoy       | 45.71°   | 34.39°    | 5.66          | 2635           |
| Salsk         | 46.43°   | 41.58°    | 14.45         | 6851           |
| Yeysk         | 46.70°   | 38.28°    | 3.34          | 1581           |
| Saky          | 45.13°   | 33.58°    | 3.46          | 1581           |

where $\eta_{STC}$—PV module efficiency under the standard test conditions (1000 W/m², AM 1.5 spectrum and PV module temperature is 25°C), $k_t (1/°C)$—power temperature coefficient.

For calculation of $N_{modj}$ needed for desalination in $j$-th month:

$$N_{modj} = \frac{W_{cons}}{S_{mod} A_j \eta_j \eta_{inv}}. \quad (4)$$

To calculate demanded area for the PV array in given location (PV module tilt angle is equal to latitude angle) the following expression can be used:

$$S_{pvj} = S_{mod} N_{modj} \cos(\varphi), \quad (5)$$

where $\varphi$—a latitude angle.

Capital costs (including inverter and mounting poles) were estimated using average data for specific costs of grid-tie PV plants around the world from [13] as $C_{sp} = 2.108$ USD/W (peak):

$$C_{pvj} = C_{sp} N_{modj} P_{peak}. \quad (6)$$

The value of $P_{peak} = 250$ W was taken as the peak power of the PV module type (according to multi-Si PV modules which are the most prevalent for different applications).

To estimate battery bank influence on capital costs, lead–acid batteries are considered to feed RO unit during the average night duration of the year (12 h) for each location. Night and day average energy consumption are taken equal to half of a daily consumption. To cover night consumption one should take into account efficiency of a battery and a charge controller (0.78 and 0.92 respectively in case of the lead–acid battery):

$$W_{cons\ night} = \frac{W_{cons}}{2 \eta_{batt} \eta_{charge}}. \quad (7)$$
Table 3. Demanded area ($S_{pv}$) and capital cost ($C_{pv}$) for the PV power unit for RO desalination in regions of Russia (yearly averaged), considering 1 m$^3$ of brackish water per day desalination.

| City            | Without battery | With battery |
|-----------------|-----------------|--------------|
|                 | $S_{pv}$ (m$^2$) | $C_{pv}$ (USD) | $S_{pv}$ (m$^2$) | $C_{pv}$ (USD) | $C_{batt}$ (USD) |
| Volgodonsk      | 7.8             | 3689         | 12.6           | 7855           | 1877            |
| Kotelnikovo     | 4.4             | 2108         | 6.0            | 3800           | 895             |
| Taganrog        | 4.4             | 2108         | 7.1            | 4427           | 1047            |
| Volgograd       | 4.3             | 2108         | 6.7            | 4307           | 1011            |
| Krasnodar       | 3.5             | 1581         | 5.3            | 3269           | 851             |
| Novorossijsk    | 17.6            | 7905         | 28.1           | 17558          | 4946            |
| Maykop          | 7.0             | 3162         | 11.6           | 7043           | 1821            |
| Stavropol       | 31.0            | 14229        | 52.2           | 32073          | 8195            |
| Mineralnye Vody | 19.9            | 8959         | 32.0           | 19330          | 4946            |
| Nalchik         | 15.5            | 6851         | 25.2           | 15185          | 4058            |
| Ordzhonikidze   | 19.6            | 8959         | 32.5           | 20549          | 5687            |
| Grozny          | 17.9            | 7905         | 28.8           | 17681          | 4946            |
| Makhachkala     | 3.6             | 1581         | 5.6            | 3366           | 810             |
| Derbent         | 14.5            | 6851         | 24.6           | 15269          | 3616            |
| Elista          | 17.0            | 7905         | 28.9           | 18382          | 4946            |
| Djankoy         | 7.9             | 3689         | 12.0           | 7563           | 1962            |
| Salsk           | 16.7            | 7905         | 28.9           | 18631          | 4946            |
| Yeysk           | 3.3             | 1581         | 5.2            | 3313           | 851             |
| Saky            | 3.5             | 1581         | 5.2            | 3285           | 851             |

Additional PV modules must be installed, because energy consumption increases:

$$W_{cons}^{total} = \frac{W_{cons}}{2\eta_{batt}\eta_{charge}} + \frac{W_{cons}}{2}. \tag{8}$$

So this new value must be substituted into (4) instead of $W_{cons}$, resulting in new solar battery area and capital costs.

Capital costs for lead acid battery are estimated as:

$$C_{batt} = \frac{W_{cons}^{night}100}{C_{sp}^{la}DOD}, \tag{9}$$

where DOD (in %) stands for recommended battery depth of discharge and $C_{sp}^{la}$—specific lead–acid battery cost (0.2 USD/Wh). This value should be added to $C_{pv,j}$ from (6).

3. Results and discussion

According to the estimation results, maps with demanded PV areas and PV power unit costs for RO desalination were compiled (considering 1 m$^3$ of brackish water per day desalination performance). Results of the estimation for the best month from insolation point of view (which is July) are given in table 2. Results for yearly average insolation taking into account battery energy storage are given in table 3. Calculation results based on an yearly average insolation are represented in figures 3 and 4.

It can be seen that demanded areas and capital costs for the PV power unit are defined both by initial water salinity and insolation. The largest PV unit area and capital costs were obtained
For Stavropol and are caused by high initial salinity (though insolation in this location is not the worst among all conditions considered). The smallest PV unit area and capital costs were
obtained for Saky in Crimea due to high insolation level and low ground water salinity there. Thereby, proper initial data on salinity level are very important for making correct economical estimations.

The yearly average results based on this approach can be used to estimate the attractiveness of PV-powered RO desalination for location as a whole. Results for the month with the maximum level of insolation can be a reference point for seasonal usage of this technology, e.g. recreation or grazing cattle breeding.

4. Conclusion
Possibilities of using PV power for water desalination in Southern Russia were investigated. As a result of the technical and economic analysis carried out, demanded areas and capital costs for PV power units were defined. It was shown that PV installations could be used for brackish water desalination with low salinity in regions with high solar insolation level. Water-storage tank application is more preferable than using electrochemical batteries due to the economic aspects. For some locations seasonal application of PV powered water desalination units is recommended.

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