Environmental Characteristics of Solar Photovoltaic Installations Use, Considering Trends of Solar Energy Generation and Sustainable Development

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Abstract: The paper contributes to the discussion on the matters of alternative and renewable energy sources integration, considering the trends of current and future development of photovoltaic solar panel technology and sustainability issues. Given the fact that sustainable development imposes strict requirements for the technologies to be environment-friendly, this research has been undertaken to verify economic (in terms of energy payback period) and ecological parameters (in terms of land use, air and water pollution, etc.) of solar photovoltaic plants, in comparison to traditional energy sources and several other renewable technologies. The key finding of the paper is the growing density of solar-power industry competition and almost total match of it to the environmental requirements of the 21st century. The latter requirement shows the Russian Federation's sustainability undermined: directly – by the backlog of technology research and development, and indirectly–by institutional and macroprudential regulations regarding solar-to-hydrocarbon technologies competitiveness.

1 INTRODUCTION

A significant increase of the share of electricity generated using renewable energy sources (RES) has been among the main trends of the world's energy-generation development in the last decade. According to the common global practices, RES include hydro, solar, wind, geothermal, hydraulic energy, energy of sea currents, waves and tides, energy of sea water temperature gradient and air/water temperature difference, energy of the Earth's heat, and the biomass of different origin (organic, household waste). However, the industrial scale of development and commercial efficiency is attributable only to wind energy, solar energy (primarily, based on photoelectric conversion), water energy, biomass and geothermal energy. Among all the types of RES, solar-energy generation is the most rapidly-developing and promising one.

According to some studies, by the mid-2050's, proved hydrocarbon reserves will be close to depletion, thus making their upstream economically irrational and causing solar energy and other renewables' growth to compensate for the decline in energy generation. Solar energy is becoming especially relevant, in the context of sustainable development strategy and policy implementation.

Since 1987, when "Our Common Future" report of the UN Commission on Environment and Development (led by G.H. Brundtland, then PrimeMinister of Norway), was published, the sustainable-development theme has been widely discussed. But still, being an object of methodology research and political declarations, practical implementation of its conceptual basics is far from being implemented.

Sustainable development is defined as a new mode of civilization based on radical changes in its historically-developed parameters (social, ecological,

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economic, etc.). It sets out the task of optimal management of both natural resource potential and the whole of society's wealth, considering its future state in a specific historical period. The priority in achieving sustainable development is to ensure decent living conditions for, and sustainable development of, individuals. This broader interpretation is, at the same time, a moral imperative, a required model of the future, and a regulation that needs to be practically implemented.

The sustainable development paradigm incorporates research and design of new energy-saving instruments and models of using renewable environment-friendly energy sources.

Resolution of questions concerning the growth of consumption has become an urgent task for the survival of mankind, stretching to the end of the century. Action is needed to restrain the consumption of hydrocarbon fuels and encourage the use of non-traditional energy sources, along with thermonuclear and hydrogen energy research and development. Further growth of hydrocarbon fuels consumption, in combination with the demographic factor, would lead to an ecological catastrophe and dehumanization of society.

Sustainable development energy-generation meets broader requirements than clean energy. The concept of an ecologically-clean energy system contains the requirement to employ inexhaustible and environment-friendly resources. At the same time, they must meet the two most important principles of sustainable development: respect the interests of future generations and preserve the environment.

Increasing emissions of carbon dioxide should foster the development of industrial power generation that employs clean, solar energy based on photoelectric conversion, to reduce environmental pollution and global warming. All these factors will contribute to the growth of solar energy's share up to 60% of the total energy consumption balance. The amount of solar energy entering the Earth exceeds the energy of all world reserves of oil, gas, coal and other energy resources, including renewables. Its potential is so great that, according to existing estimates, the solar energy reaching Earth every hour is enough to meet the current annual need for energy globally. In this regard, the role of research aimed at revealing the ecological characteristics of devices, used in solar energy, is being updated.

2 ASSESSMENTOF SOLAR PHOTOVOLTAIC FACILITIES' ENVIRONMENTAL IMPACT

2.1 Ecological Parameters of Solar Photovoltaic Facilities' Impact

Depending on the principle of solar energy conversion, power plants are divided into photovoltaic (SPVP–solar photovoltaic plant) that employ the method of direct (machine-free) conversion of solar energy into electric energy using photovoltaic converters (PVC), and thermodynamic (STDP–solar thermodynamic plant) in which solar energy is first converted into heat that is further transformed in thermodynamic cycle tokinetic energy, and then in a generator becomes electric energy. The subject of this study is solar energy generation based on photovoltaic conversion–a rapidly growing industry and technology.

Special attention to environmental characteristics is necessary since it is a key factor in decision making on solar energy infrastructure development. This infrastructure facilitates to significant decrease of anthropogenic impact of modern civilization and its ever-growing energy needs. Global best practices indicate that an assessment of such a technology's impact is made using an integrated approach known as "Life Cycle Assessment" (LCA) covering three main stages that correspond to the proper characteristics (see Table 1).

Table 1: Ecological characteristics appropriate to different stages of an SPVP life-cycle (International Energy Agency, 2011)

Lifecycle stage	Characteristics
Manufacture	Toxic and contaminant materials used in SPVP manufacture
	Energy consumption, including energy from thermal power plants
	Water consumption and quality of its filtration
Use	Energy efficiency of a technology – Energy Payback Period, i.e. the period required for a newly-activated energy system to generate the same amount of energy (in terms of primary energy equivalent) that was used to produce the system itself
	Pollution and environment contamination indicators
	Land and other natural resources use, influence on biodiversity
Utilisation and recycling	Safety of facility utilization after expiry or failure

In case of SPVP, such analysis can be held in a simplified mode, since it employs zero-emission technology and requires almost no maintenance cost: only stages of photovoltaic modules manufacture and an SPVP setup require special attention, since they entail raw-materials extraction and mining, construction works, etc., as well as the recycling stage, which is needed after an expected 25-year life of a facility.

In case of using photovoltaic modules, based on crystalline silicon technology (more than 80% of the market), most of the electricity costs occur at the stage of production of high-purity silicon of "solar quality". Thin-film technologies require significantly less energy to produce photovoltaic modules, since the amount of semiconductor materials, required for their production, is about 100 times smaller. In addition to raw materials consumed to manufacture a semiconductor layer of photovoltaic modules, one also should consider aluminium, iron and zinc, since they are used to produce special aluminium frames and bearing constructions, sand for glass, copper for cables and similar components to manufacture inverters.

2.2 Toxic Materials Use in SPVP Manufacture

There are several different technologies of photovoltaic-modules manufacture, and each of them employs different processes. The most common hazardous chemicals involved in crystalline silicon photovoltaic modules’ production are:

- silicon tetrachloride, which is a toxic waste of crystalline silicon production using silane gas; silicon tetrachloride can be recycled back into silane, otherwise it is a potentially dangerous substance;
- sulphur hexafluoride, used to purify the reactor employed in silicon production; in the event of leakage it emits a very strong greenhouse gas, as also, it can react with silicon to create several other potentially-hazardous compounds;
- a number of other chemicals used to purify silicon and a photovoltaic converter.

Small quantities of aluminium and silver are also consumed to manufacture components of an SPVP module. The use of lead-based solder can cause contamination problems, if these components are sent to waste landfill, or incineration. Therefore, modern manufacturers mainly use lead-free solder (Silicon Valley Toxic Coalition, 2009).

It should be noted that the same materials and substances are used in the manufacture of other electronic products, such as computers and TVs; Thus, the broadly-defined industry of electronic components requires the development and implementation of means of control over their disposal, to solve potential ecological problems.

Thin-film technologies based on cadmium telluride (CdTe) contain cadmium, which is one of the most toxic substances. It is prohibited in some countries (particularly in the EU), except when cadmium is used in the form of cadmium telluride. This is a stable, water-insoluble, non-metallic compound, with a melting point of 1,050 degrees centigrade, which eliminates the risk of adverse effects on the environment proved by appropriate tests. Notably, one NiCd battery for home appliances contains 2,500 times more cadmium than one photovoltaic module; production of 1 kWh of electricity by a coal-powered generation facility emits 360 times more cadmium than is contained in photovoltaic modules needed to produce 1 kWh of electricity (Silicon Valley Toxic Coalition, 2009).

2.3 Water Use

Electricity production is a process associated with the intensive use of water resources. In the US, electricity production accounts for more than 40 percent of all daily freshwater consumption. SPVPs do not require water for power generation. Zero water consumption provides SPVP with an additional advantage in those places where there is a shortage of water, since it does not put additional pressure on local water resources (Union of concerned scientists, 2013). Nevertheless, when analysing this factor over the whole life cycle of an SPVP, it is necessary to consider that water is used for PV modules production, as for other manufacturing processes, although its consumption is minimal. Studies have reported that water consumption throughout the life cycle of an SPVP is minimal (no more than 15 litres per MWh), compared to other electricity generation technologies. The only technology that has lower water consumption is wind energy technology (4 litres per MWh). Significantly-higher amounts of water consumption are attributable to coal-based generation (1140 litres per MWh), nuclear power (1500 litres per MWh), hydrocarbons (1100 litres per MWh)(Canada Clean Energy Fund, 2013).

2.4 Energy Efficiency and CO_2 Emission Decrease

According to the majority of experts, the value of "energy payback period" (EPBT) for an SPVP, in the current phase of technology development, is about 1.3 years with a service life of at least 25 years (Greenpeace, 2012). In fact, this is an equivalent of Energy Return on investment (EROI) at 1:19, which makes this technology equal in efficiency to oil and gas upstream (from 1:19 to 1:32 depending on the degree of recovery). Due to technological improvement, this indicator for an SPVP has significantly improved over the past 5 years. According to some studies, any technology in the energy sector must beat the 1:14 indicator to be efficient in the long run (Lambert et al., 2012). Thus, it can be stated that, during approximately 23 of 25 years of an SPVP's lifecycle, it generates electricity without any emissions into the environment.

Several sources say that the harmful emissions of SPVPs, based on the most energy-consuming technology of crystalline silicon, are equal to 33-50 g/kWh of CO_2 equivalent (for thin-film technologies, this value is 18 g/kWh), while coal-consuming power plants emit 796.7 g/kWh, fuel oil-consuming plants – 525 g/kWh, and gas-consuming plants – 377 g/kWh. Judging by this indicator, solar energy has about 10-20 times less impact on the environment for the entire life-cycle period (Greenpeace, 2012). Moreover, as mentioned above, major emissions occur at the stage of photovoltaic modules and other SPVP components' production (Table 2).

Combustion of hydrocarbon fuel remains the world leader of harmful emissions into the atmosphere. Solar energy, in most cases, is perceived as a technology with practically zero emissions, which is confirmed by calculations. Some studies also analyse the effect of SPVPs on harmful emissions to the atmosphere, throughout the life cycle. They indicate that throughout SPVP's entire life-cycle, the unit emission of greenhouse gas varies from 16 to 86 grams of CO_2 equivalent per kWh generated, while replacement of fossil fuels can deliver reduction in emissions from 650 to 850 grams of CO_2 equivalent per kWh (Ministry of New and Renewable Energy, 2013).

Thus, we conclude that SPVPs have a significant positive effect on reducing harmful emissions to the atmosphere, throughout the life cycle of the plant, while their energy payback indicator is currently the same as hydrocarbon recovery technologies, considering their gradual depletion and deterioration in recoverability.

2.5 Land Use

Depending on the location and type of an SPVP, the environmental impact, regarding this criterion, should be assessed in different ways. Thus, large SPVPs, located on the ground, can cause risk of land degradation and habitat loss for local fauna. A site area required varies, depending on the technology, terrain specific, the site shape, the latitude and other factors. On average, the required area for an SPVP placement is 2 to 4 hectares per 1 MW of power. When placed on artificial surfaces, e.g. on the roof of a building, an SPVP does not require additional space.

Land use parameters of SPVPs raise concerns about the potential impact of such projects on land and on natural habitats of fauna. This issue is resolved through regulated examination of each project. Preference is given to projects that are located on land plots of various abandoned facilities (airports, mines etc.). In this case the potential environmental impact can be significantly reduced and even have a positive effect of land rehabilitation and economic reactivation of abandoned land.

Critics of solar energy often claim that SPVPs require more land than traditional generation technologies such as coal and natural gas. Similar criticisms are also put forward against wind farms.

Nevertheless, certain evidence has been published that large SPVPs in areas with high solar insolation use less ground than some traditional energy sources, such as coal generation, considering the use of land throughout the life cycle of the technology (for example, the land required for development of coal mines). Considering the extraction, transportation and utilization of non-renewable energy sources in calculating the required land area, SPVPs become comparable in this regard. At the same time, installations located on the roof do not take any additional space at all, while their share in the total installed capacity of solar energy is more than 80%. A comparison of the use of land for various technologies is presented in Table 3.

Traditional energy sources use is often associated with soil acidification, through precipitation from hydrogen, sulphates, nitrates of sulphuric acid, nitric acid and acid rain. Acid precipitation is mainly due to the combustion of fossil fuels. Rehabilitation of lands contaminated by acid precipitation or harmful substances can take decades and, in some cases, even centuries.

Table 2: Unit energy consumption by different components of an SPVP.

	Silicon	Ingot	Plate	Cell	Other components	SPVP
Electricity consumed	80-150 kWh/kg	7-9 kWh/kg	2 kWh/kg	0,15-0,2 kWh/W	0,02 kWh/W	0,15 kWh/W
Electricity consumption share	56-72 %	4-5 %	2-3 %	12-14 %	1-2 %	9-20 %

Compiled by authors from (Greenpeace, 2012)

Table 3: Comparative data on the land use by different energy generation technologies.

Energy sources	Land use, square meters per MWh	Remarks
Natural gas thermal facility	0,45	Not including land use for fuel production
Coal thermal power plant	4,4-5,8	
Nuclear power plant	6,0	
SPVP	9,0-14,3	
Windfarm (land may be shared with agriculture)	69-94	Not including possible land use shared with agriculture
Hydroelectric power station	122	
Biomass thermal power station	360-488	Not including land used to store organic waste

Compiled by authors from (CanadaCleanEnergyFund, 2013)

Compared with traditional types of energy generation, soil acidification from an SPVP during its life-cycle is insignificant. One should consider only power-generation required to produce components of solar power plants (Canada Clean Energy Fund, 2013).

2.6 Influence on Biological Diversity

Assessing the negative impact on flora and fauna, it is necessary to consider each project separately, since the degree of this influence strongly depends on local conditions and features. There are cases when the territory around SPVPs is used for other needs, like grazing.

Recent studies have shown that construction of large SPVPs can have a positive impact on the landscape, natural conditions, flora and fauna in comparison with the production of electricity based on fossil fuels. SPVPs have a significant potential for positive impact on local flora and fauna. They can contribute to depopulation of undesirable species, while ensuring appropriate conditions for the habitat of endemic species (Turney & Fthenakis, 2011).

In December 2010, the German Renewable Energy Agency completed a draft study on the impact of SPVPs on biodiversity. The results show that SPVPs can increase the number of species in a given area. When SPVPs are designed responsibly, they can create new habitats for endangered animals and plants and engage abandoned, or unused, land in economic cycle. In 2005, the German Nature Conservation Association and the Solar Energy Association of Germany developed requirements that should be met in the design and construction of an SPVP (Canada Clean Energy Fund, 2013):

- local environment monitoring and compensatory measures after implementation of an SPVP project;
- local environmental planning specialists' involvement;
- soil sealing (i.e. covering with an impermeable material) tolerance of not more than 1% of the surface;
- correct choice of crops, to ensure the preservation of local genetic diversity;
- avoiding negative consequences of fencing-out a plant;
- development of an appropriate environmental-monitoring program for an SPVP location.

2.7 Safe Utilization and Recycling

After an SPVP (and particularly its photovoltaic modules life cycle) expires, as well as of any other electronic equipment, it is necessary to provide for the possibility of recycling. Notably, recycling and utilization are the most important issues, from the environmental impact point of view. Appropriate legislation has been adopted, or is being developed, in many countries. Major manufacturers of photovoltaic modules announced programs of free disposal of faulty items. They joined the European initiative PVCYCLE, which aims to increase the utilization rate to 85% by 2020. The first large enterprise specialized in photovoltaic cells processing was opened in 2009, as part of the PVCYCLE program.

Obviously, development of solar energy production, based on photovoltaic conversion, has much less negative environmental impact than traditional power generation based on the combustion of fossil fuels. Comparing SPVPs with traditional methods of power generation, in terms of the impact on the environment, it can be postulated that the amount of harmful emissions into the atmosphere and waste is insignificant: water consumption is minimal throughout the life cycle. Land resources use, albeit being significant, influences soil condition slightly and does not require further rehabilitation.

On the other hand, growth of the solar power plant industry may have its own environmental consequences. For example, increasing the production of photovoltaic modules, considering the need for operation and disposal, can create a large volume of so-called electronic waste. The decommissioning phase of an SPVP life-cycle is the most important, regarding the environmental impact assessment. Nevertheless, programs of photovoltaic modules' utilization have already been launched and have shown their efficiency in reducing the harmful impact on the environment.

Certainly, taking a decision to stimulate the development of solar energy based on photovoltaic conversion, it is necessary to consider all the characteristics described above: technical, socio-economic and environmental. It should be noted that, regarding the explicit advantages, technical and ecological issues of solar energy should contribute to its demand and make it a significant part of the world energy generation, although it cannot become the only source of energy due to several known constraints. At the same time, assessment of solar energy potential, competitiveness and consequences of its development from the ecological and economic point of view enables us to make a balanced decision on the necessity of its development, considering the possible supply and demand in a specific territory of the Russian Federation.

Comparative characteristics of the main technical, economic and environmental issues regarding all major types of energy are listed in Table 4.

Table 4: Main power generation technologies compared across generalized technical, economic and environmental characteristics.

Characteristics (positive)	Main energy generation technologies							
	Traditional		Renewable					
	Thermal	Nuclear	Hydro	Wind	SPVP	Small hydro	Bio	Geothermal
Technical								
Potentially inexhaustible source	-	-	+	+	+	+	-	+
Distributed generation - closer to the consumer	-	-	-	+	+	+	+	+/-
Dispatchability, no need to accumulate	+	+	+	-	-	+/-	+	+
High concentration of production	+	+	+	-	-	-	-	-
Co-generation (generation of thermal energy of high potential)	+	+	-	-	-	-	+	+
Potential for further development of technology	-	+/-	-	+	+	+/-	+/-	+/-
Economic								
Independence from fossil fuels	-	-	-	+	+	+	+	+
Potential to reduce production costs	-	-	-	+	+	+/-	+/-	+/-
Ecological								
Zero emission and waste during generation	-	+/-	+	+	+	+	+/-	+
Minimal damage to water and land resources	-	-	+/-	+	+	+/-	+	+

It is obvious, that SPVPs are not the best power-generation technology, given the capacity constraints, ecological issues and, for example, demand-side factors like intermittency. Still, the comparative features of available technologies enhance the search for their optimum combination, to cover the needs of a specific territory.

The photovoltaics industry is experiencing an exponential growth worldwide, which becomes another determinant of the development sustainability. This time, it is in economic terms of a country's competitiveness. Countries of Europe, North America and Asia deploy projects aimed to support the mainstream of photovoltaic industry development (see the USA "Million Solar Roofs" project, or the Chinese 2011 five-year-plan for energy production, which included renewables). The technology is being researched, mastered, improved and patented, which makes it more difficult to replicate, but easier to promote and sell abroad. In this context, the Russian segment of photovoltaic industry can rapidly lose its pace, especially in the household-supply segment of the market (Akhmetshin et al., 2018), and be ranked far behind the world's leaders, which are manufacturing SPVPs at much lower cost.

Although forecasts on the photovoltaic growth are unclear and difficult to compile, there is an ascending worldwide trend in the use of photovoltaics: today, China takes the first place in photovoltaics power production, while India and the US are expected to be, along with China, the largest markets for solar photovoltaics installations in the next decade (European Photovoltaic Industry Association, 2014).

Forecasts say, "by 2022, global photovoltaic generation capacity will likely reach 871 gigawatts. That is about 43 gigawatts more than the expected cumulative wind installations by that date. Also, it is more than double today's nuclear capacity" (Lacey, 2017).

Further evidence of the rapid growth of the photovoltaic industry, found in the latest IEA report, stating that its earlier forecasts underestimated the PV deployment: SPVP deployment costs reduction and growing fashion all over the world made IEA re-evaluate the 2050-forecast of photovoltaics share in the global energy generation from 11% stated in 2011 up to 16% stated in 2014 (International Energy Agency, 2014). Forecast verification can easily be found in regional prospects. The Clean Edge research indicates that "the solar contribution could be quite considerable, realistically reaching 10 percent of total U.S. electricity generation by 2025, by deploying a combination of solar photovoltaics and concentrating solar power" (Clean Edge, 2008). Moreover, according to regional forecasts, long-term growth is anticipated in China, India and Japan.

The Russian Federation's programs of sustainable development declare changes in the balance of energy delivered and consumed, but the industrial side stumbles due to several institutional (Nestereko et al., 2018) and macroprudential (Ekimova et al., 2017) constraints that need to be overcome.

3 CONCLUSIONS

Solar energy from SPVPs meets the basic requirements of sustainable development: energy security, accessibility and environmental friendliness. Considering the high potential of technology development and cost reduction, this type of energy is the most promising one. At the same time, the obvious technical advantages of traditional energy generation (dispatchability, high concentration of production, the possibility of co-generation) make it indispensable in terms of providing energy to industry and large cities, which is attributable to the industrial stage of civilization development.

In the context of post-industrialization and de-urbanization, which responded to the challenges of the new century, solar energy along with other renewable energy generation technologies can become one of the technological and infrastructural bases for development of the new-mode economy and society in the Russian Federation.

Given the speed of these processes' development, as well as the obvious need to preserve industrial potential during the post-industrial era, solar energy development will need to be rationally combined with traditional energy sources, the latter gradually decreasing its share in the energy balance.

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