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SOLAR THERMAL POWER PLANTS IN THE WORLD: THE EXPERIENCE OF DEVELOPMENT AND OPERATION

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ABSTRACT

The main areas of large-scale development of solar energy are:

- conversion of solar energy into low-grade heat, and using the latest in heating systems of residential, municipal facilities, public and industrial buildings that consume energy such as temperature capacity;

- conversion of solar energy into electricity through photovoltaic and thermodynamic converters.

This report provides short information of the dynamics of the creation and operation of solar power plants (SPP) with the thermodynamic conversion, and the criteria for reducing cost of electricity produced from them.

Key words: *renewable energy sources, solar energy, solar power plant, parabolic trough, integrated solar combined cycle*

1. INTRODUCTION

In the world practice a view to obtaining electrical energy with the help of thermodynamic conversion of solar energy (SE), the following technologies are used: parabolic through collector (PTC), linear Fresnel, dish Stirling and solar tower [1].

On the basis of the abovementioned technologies today in the developed countries of the world are created big capacities solar power plants. In [1-3] are considered indicators the operational SPP solar tower and parabolic trough which capacity 100 MW and above.

SPP with the thermodynamic conversion of SE operated mostly in the range of 35° S - 35° N, but on research of executed in [4] PTC with the orientation of the optical axis of the north-south for the winter declination of the Sun can also be used in areas between 40° S - 40° N.

Together with it, on a row with the purely thermodynamic transformation of SPP, are created integrated solar combined cycle (ISCC) power plants. In table 1, the lists of the ISCC with PTC installed in the period from 2009 to 2015. Accordingly, in table 2 is a list of the planned ISCC to 2020 worldwide.

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Table 1. List of operational ISCC based on PTC in the world

Project Name	Electric power, MWe	Solar Capacity MWe	Country	Technology	Operation year
Martin	3705	75	USE	Parabolic Trough	2010
Victorville	563	50	USE	Parabolic Trough	2013
Agua Prieta	480	31	Mexico	Parabolic Trough	2015
Ain Beni Mathar	472	20	Morocco	Parabolic Trough	2010
Yazd	430	67	Iran	Parabolic Trough	2009
Kuraymat	140	20	Egypt	Parabolic Trough	2011
Hassi R'Mel	130	25	Algeria	Parabolic Trough	2011
Archimede	130	5	Italy	Parabolic Trough	2010

According to the data [5], in the world leaders in terms of development and operation of SPP are USA, Spain, South Africa, Morocco, Chile, China, India, and Israel. The total number of operation and under construction until 2019 SPP are shown in Table 3.

As can be seen from Table 1 and Table 2, the capacity of solar part of ISCC is from 5 to 20% of the total capacity of the whole plant [3].

Table 2. List of planned ISCC based on PTC until 2020 in the world

Project Name	Electric power, MWe	Solar Capacity MWe	Country	Technology
Elmed CSP – Project	1200	100	Tunisia	Parabolic Trough
Waad Al Shamal ISCC Plant	1050	50	Saudi Arabia	Parabolic Trough
Palmdale	555	62	USA	Parabolic Trough
Hassi R'Mel II	400	70	Algeria	Parabolic Trough
Meghaier	400	75	Algeria	Parabolic Trough
Naama	400	70	Algeria	Parabolic Trough
Al Abdaliyah ISCC	280	60	Kuwait	Parabolic Trough

Table 3. Operational and planned solar power plants based on the thermodynamic conversion of solar energy (until 2019) in the world

Project Name	Technology	Total Capacity MW	Solar Capacity MWe	Country	Current Status	Storage (Hours)	Actual Commercial Operation Date	2015 USD (constant millions)
Nevada Solar One	Parabolic Trough		64	USA	Operation	0.5	01/06/07	$258
Spain PT w/ 7.5 h storage	Parabolic Trough		50	Spain	Operation	7.5	01/12/10	$405
Martin Next Generation Solar Energy Center	Parabolic Trough		75	USA	Operation		01/12/10	$462
Shams 1	Parabolic Trough		100	UAE	Operation		17/03/13	$588
Solana	Parabolic Trough		280	USA	Operation	6	09/10/13	$2,041
Enerstar Villena	Parabolic Trough		50	Spain	Operation		01/11/13	$309
Genesis Solar 2	Parabolic Trough		125	USA	Operation		30/11/13	$499
Ivanpah Solar Electric Generating Station I	Tower		126	USA	Operation		30/01/14	$732
Ivanpah Solar Electric Generating Station II	Tower		133	USA	Operation		30/01/14	$732
Ivanpah Solar Electric Generating Station III	Tower		133	USA	Operation		30/01/14	$732
Genesis Solar 1	Parabolic Trough		125	USA	Operation		01/03/14	$499
Megha	Parabolic Trough		50	India	Operation	8	12/11/14	$127
Mojave Solar Project	Parabolic Trough		280	USA	Operation		01/12/14	$1,633
Crescent Dunes	Tower		110	USA	Operation	10	01/01/15	$964
KaXu Solar One	Parabolic Trough		100	S. Africa	Operation	2.5	02/03/15	$843
Bokpoort	Parabolic Trough		50	S. Africa	Operation	9.3	17/12/15	$323
Khi Solar One	Tower		50	S. Africa	Operation	2	01/01/16	$432
Noor I	Parabolic Trough		160	Morocco	Operation	3	04/02/16	$1,163
Atacama-1 (Planta Solar Cerro Dominador)	Tower	210	110	Chile	Construction	17.5	01/06/17	$1,275
Shagaya CSP Project - Phase One	Parabolic Trough		50	Kuwait	Construction	9	01/07/17	$257
Noor II	Parabolic Trough		200	Morocco	Construction	7	01/07/17	$1,100
Akesai Solar Thermal Power Plant	Parabolic Trough		50	China	Construction	15	01/08/17	$318
Xina Solar One	Parabolic Trough		100	S. Africa	Construction	5	01/09/17	$652
Noor III	Tower		150	Morocco	Construction	7	01/10/17	$861
Qinghai Delingha (CGN) Phase I	Parabolic Trough		50	China	Construction	7	31/12/17	$397
Ashalim Plot B (Megalim Solar Power)	Tower		121	Israel	Construction		31/12/17	$735
Kathu CSP	Parabolic Trough		100	S. Africa	Construction	4.5	01/06/18	$716
Ashalim Plot A (Negev Energy)	Parabolic Trough		110	Israel	Construction	4.5	01/07/18	$980
Ilanga CSP 1 (Karoshoek Solar One)	Parabolic Trough		100	S. Africa	Construction	5	01/10/18	$592

Table 4 shows the technical and economic indicators of the solar power plant with thermodynamic conversion based on different technologies.

Table 4. Solar thermal power plants type

	Line Focusing		**Point Focusing**	
Technology	**Parabolic Through**	**Fresnel**	**Solar Tower**	**Dish**
Capacity (MW)	10~200	10~200	10~100	0.1~1
Efficiency (%)	11~16	13	7~20	12~25
Temperature (°C)	350~415	270~500	250~565	750~800
Investment (USD/kW)	3,000~6,500	2,500~5,500	4,000~6,000	4,000~10,000
Status	Commercialized	Commercialized	Commercialized	Prototype
Market Share	90~93%	Small	5~7%	Small
Remarks	HTF, Molten salt	Water/steam cycle (Clean, Min. Heat exchanger)	Air, Water, Molten salt (gas turbine & CC)	Rankine cycle/Stirling engine

As seen in table 4, solar thermal power plants based on PTC dominate around the world.

2. MATERIAL AND METHOD

Created in the world ISCC based on PTC are generally designed as in fig. 1. ISCC consists of the gas turbine with natural gas as combustible fuel, heat recovery steam generator (HRSG), steam turbine, cooling system and the solar field from PTC. The plants presented in Table 1 and 2 are under construction according to the schematic diagram provided on fig. 1 [6].

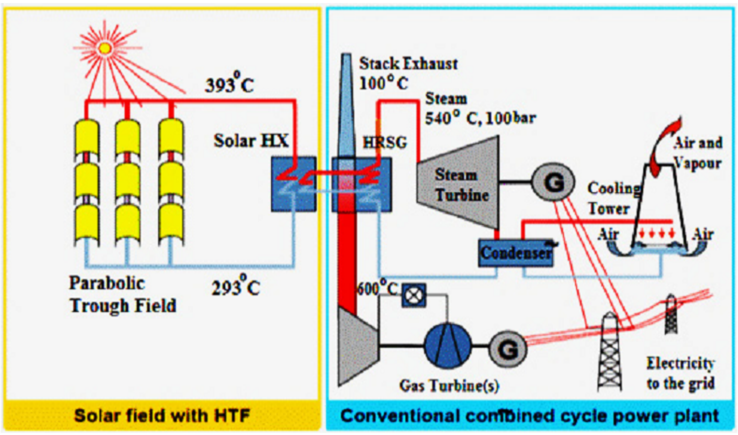

Figure 1. ISCC system schematic diagram

Generalization of operating experience shows that in ISCC, the electric solar capacity does not account for more than 15% of the electric steam turbine capacity of the ISCC. This limitation is necessary in order to avoid considerable negative effects on the Rankine cycle efficiency during times of no or low solar irradiation.

The steam turbine of the ISCC has to be designed for maximum solar heat, i.e. it will be larger than in a CC with the same gas turbine. Hence, at operating points with no solar irradiation the steam turbine will operate in part load conditions whereas in the CC it would operate at full load. Usually, from 100% to 85% of the nominal load the efficiency of the steam turbine is approximately constant. Hence, by limiting the Electric Solar Capacity to 15% the negative effects of increased part load become negligible [7].

As it is specified in [8,9], now the electricity produced by large photovoltaic systems in Germany costs cheaper, than 9 Euro cents for kWh that is comparable with the electric power developed by coal and gas thermal power plants at prime cost from 5 to 10 Euro cents for kWh. Prime cost of the nuclear energy developed by the modern nuclear power plants (NPP) according to them makes 11 cents for kWh.

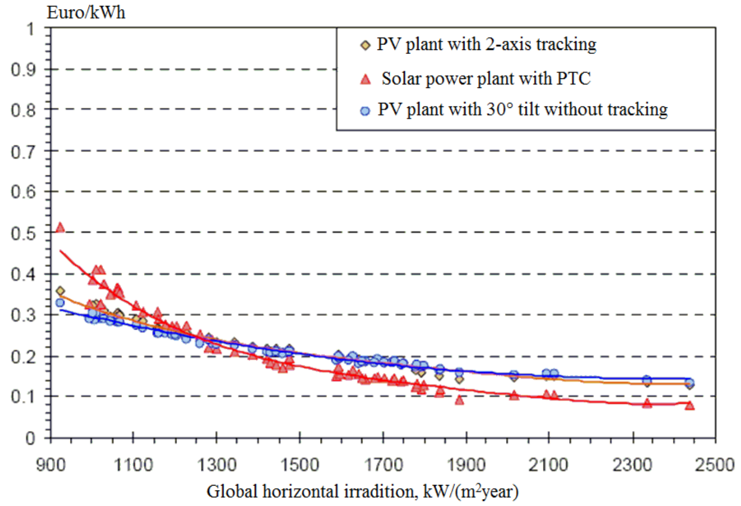

Figure 2. Cost price of the generated power energy on solar power plants

On the chart 1 is shown Global CSP Capacity (MW_e) by technology and status [10].

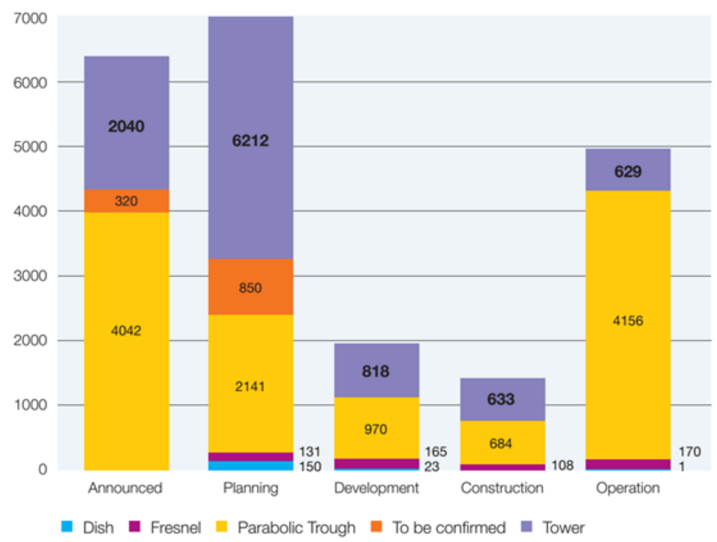

Chart 1. Global power of CSP (MW_e)on technology and the status

Cost price of the electric energy, generated by solar thermal power plants is in range of 12-18 Euro cents for kWh that does it to one of the least expensive options for increase in the generating capacities (Fig. 2.). According to forecasts cost price of the electric energy generated on solar thermal power plants in Central and Southern Europe, as expected, will decrease to 8-12 Euro cents for kWh by 2030 (fig. 3) [9].

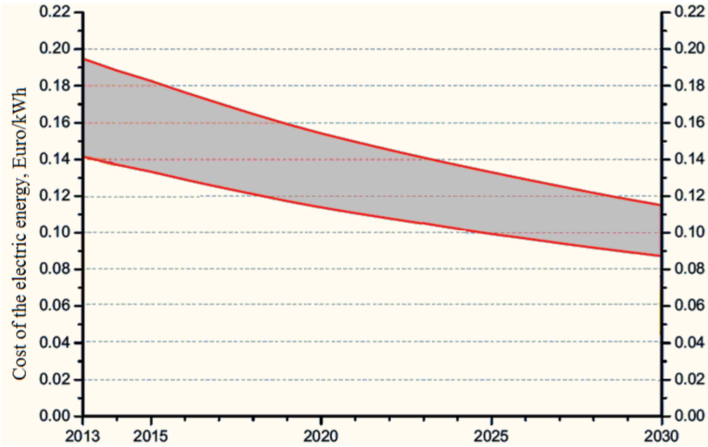

Figure 3. Forecast of decrease in cost price of electrical energy generated in solar thermal power plants at solar radiation in 2000 ÷ 2500 (kW/(m^{2}y))

Table 5 lists the current and expected costs of the main systems of a typical solar thermal power plant [11].

Table 5. Drivers for cost reduction in ISCC

	Today	2025
A) Solar field incl. HTF (€m^2)	160 – 250	100 – 160
B) Thermal Storage (€/kWh$_{th}$)	26 – 30	18 – 21
C) PowerBlock (€/kW$_e$)	720 – 765	700 – 790
D) System Efficiency	15%–17%	18% – 20%

The following criteria is expected to reduce costs by table 5:

A) Solar Field

1. Collector with larger Aperture (trough)
2. Improved optics through higher accuracy heliostats, improved field layout (tower)
3. Advanced assembly procedure, industrialized assembly, industrial automatization in manufacturing; (sub) supplier standards; standardized design
4. Higher reflectivity, higher cleanliness
5. Improved durability
6. Improved absorber coating
7. Wireless power supply and control (heliostat)
8. Improved optics through higher accuracy heliostats, improved field layout (tower)
9. Improved O&M procedures

B) Thermal Storage

1. Direct storage concept (HTF = Storage Medium)
2. Higher temperature difference
3. Adapted thermal storage materials
4. Standardized design; sub-supplier design standards
5. Advanced charging and discharging, improved operation strategies in general

C) Power Block

1. Higher cycle efficiency
2. Improved hybridization concept
3. Larger power block
4. Standardized design

D) System Efficiency

1. Higher process temperature
2. Lower parasitic consumption (higher temperature through larger aperture and other HTF; at the tower: gravitational pressure loss recovery)
3. Adapted turbine design (for daily start-up)
4. Improved control and O&M strategies/procedures

Based on the foregoing can be stated that the use of ISCC power plant with PTC in countries with hot climate, today the world is one of the perspective ways of for the production of electricity as from the power energy point of view and from an economic point of view.

Today in the republic is developed the Roadmap "Republic of Uzbekistan: Solar Energy Development" in assistance with the Asian Development Bank (ADB). According to the optimistic scenario in Uzbekistan until 2031, it will be installed 4 GW capacity of solar power plants, where is planned construction of solar PV plants and ISCC based on PTC. Based on the abovementioned Roadmap is scheduled construction of the first ISCC in Navoi region with a total capacity of 130 MW [12,13].

Taking into account the our country climatic conditions by us proposed the following scheme-technological solution for the creation of ISCC based on PTC in the Republic.

In fig. 4 it is presented ISCC based on PTC which consists of two gas turbine units, two HRSG, solar heat steam generator, steam turbine unit and the solar field from PTC [14].

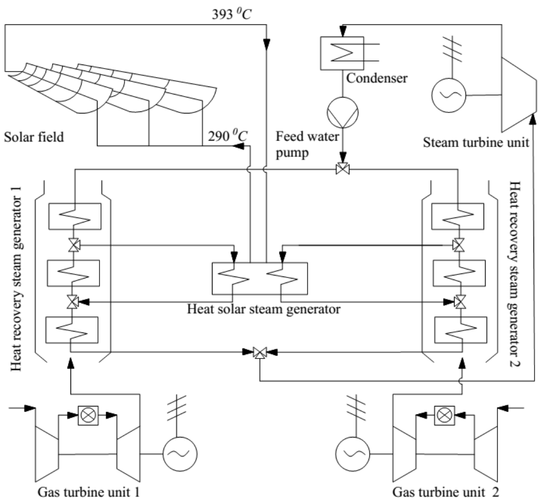

Figure 4. ISCC system schematic diagram based on PTC

Designed power plants of this type can work in three modes: ISCC mode at solar hours (even with one gas turbine), conventional combined cycle mode at non solar hours and gas turbine mode when the steam turbine is not functioning.

According to results of preliminary calculations, in the presence of the territory for the construction of the solar field (at the rate of 2 hectares per 1 MW) modernization of thermal power plants with CCGT (Navoi, Tashkent and Talimardjan), the total capacity of about 2 GW today, combining them with solar field of ISCC power plant with PTC (~ 14% efficiency), will provide the SE share from 13 to 15% of the total plant capacity and natural gas savings will be from 418 mln. m^3 to 482 mln. m^3 per year, which in turn will lead to a reduction in CO_2 emissions per year from 106.1 mln. kg to 139.2 mln. kg.

3. CONCLUSION

Our future, substantially, depends on application of technological innovations. According to forecasts, within the next decades value and a share of SE in the general process of energy production will grow rapidly. These technologies reduce not only CO_2 global emission, but also give necessary stability to power energy, doing it less dependent on limited reserves of fossil fuel.

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