Design of New Generation Multi Solar Power Stations

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1. Introduction

In the present notes, we're going to report some considerations and rough estimates of the performance of an hypothetical combined photovoltaic-solar thermoelectric plant proposed by Millennium Electric. The plant is designed to combine photovoltaic (PV) and thermo-solar (TS) electric generation. In particular, the starting point is the use of cooled photovoltaic modules. Cooling enhances the photovoltaic module efficiency, and the cooling fluid can be exploited in a Rankine cycle, producing further power. However, the cooling water temperature at the exit of PV system is rather low (55°C). Thus, since the Rankine cycle efficiency is strongly dependent on the temperature level, a set of thermal solar modules is added, in order to raise the maximum cycle temperature. According to Millennium data sheet, using relatively low cost flat thermal modules, we can attain 135°C as maximum cycle temperature. Thermal storage is obviously required in order to stabilize the thermal cycle temperatures.

A sketch of the plant, given in Fig.1, shows the two set of solar panels, PV and TS. The condensated operating fluid of the thermal power plant exits the condenser at a temperature Tc slightly higher than ambient temperature, and at the corresponding vapor-liquid equilibrium pressure pc. Extraction and feeding pumps increase its pressure up to the turbine inlet pressure pit. The PV cooling water releases its exceeding heat to the low temperature storage LT. The Rankine compressed liquid is thus heated at T1 by the same LT storage. A second, high temperature, heat storage HT is heated by the water from the thermal solar panels, and provide the heat flux required to evaporate the cycle operating fluid and heat the superheated vapour up to temperature Tit. The resulting vapor is then sent to the steam turbine and the condenser. The steam latent heat is removed by the condenser cooling fluid which, in turn, is cooled either in evaporating tower or (at night) using the solar panels themselves as radiating heat sinks.

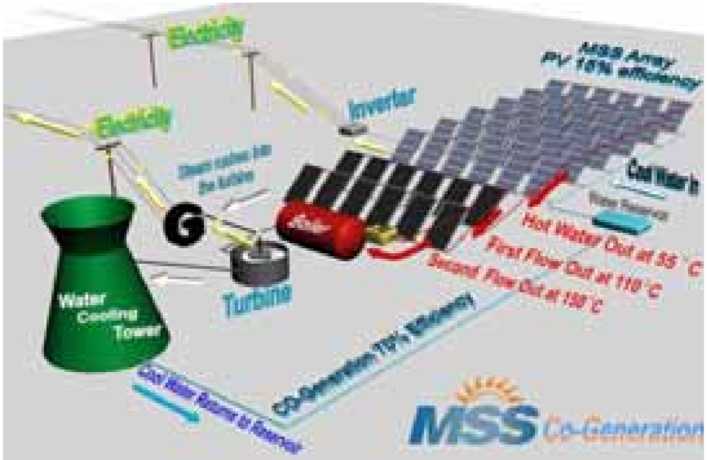

Fig 1 -MSS Co-Generation

Sample combined power plant

To further clarify the power plant operations, let us consider a sample application, designed for a PV peak power of the order of 1 MWe, and an additional thermal power from the turbine of the same order of magnitude. The following results will obviously be largely dependent on some assumption on the single component efficiencies and performances: namely, among others, turbine efficiency, thermal storage reliability, allowed temperature jump between operating fluid and storage should be verified for each single actual plant design, together with the proper economic analysis.

Using water as the Rankine operating fluid, the main design parameters are listed in the following Table 1.

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(1) **Multi Solar System (MSS)** Millennium's patented technology simultaneously produces electricity (PV cells), hot water (thermal collector components) and hot air at high efficiency. The electricity and hot water can be used for various functions including hot water, hot air for space heating/space cooling by air/heat exchange conditioning technology and electricity for lighting and home appliances. Energy storage technology is used in off-grid applications.

Table 1 **– Sample plant boundary conditions and constraints**

Steam Turbine estimated nominal power *PT*	$= 1\ MW$
Inlet turbine steam temperature *Tit*	$= 130°C$
Condenser temperature *Tc*	$= 30°C$
LT storage exit temperature T1	$= 50°C$
um Carnot efficiency	$\eta_{max} = 1 - Tit/Tc$ $= 1 – (30+273)/(130+273)=0.25$
Nominal radiation	$qi = 1\ Kw/m^2$
PV modules surface	$SPV = 8{,}000 m^2$
Solar Thermal surface	$STS = 4{,}000 m^2$
PV modules efficiency	$\eta_{e,PV} = PPV/qi = 12\%$
Incoming peak radiation	$qi = 1\ kW/m^2$
Heat recovery efficiency from PV: *qr,PV* : heat flux available from PV cooling system	$\eta_{r,PV} = q_{r,PV}/q_i = 70\%$
Heat recovery efficienty from TS: *r,TS* : heat flux available from thermal solar panels	$\eta_{r,TS} = q_{r,TS}/q_i = 90\%$

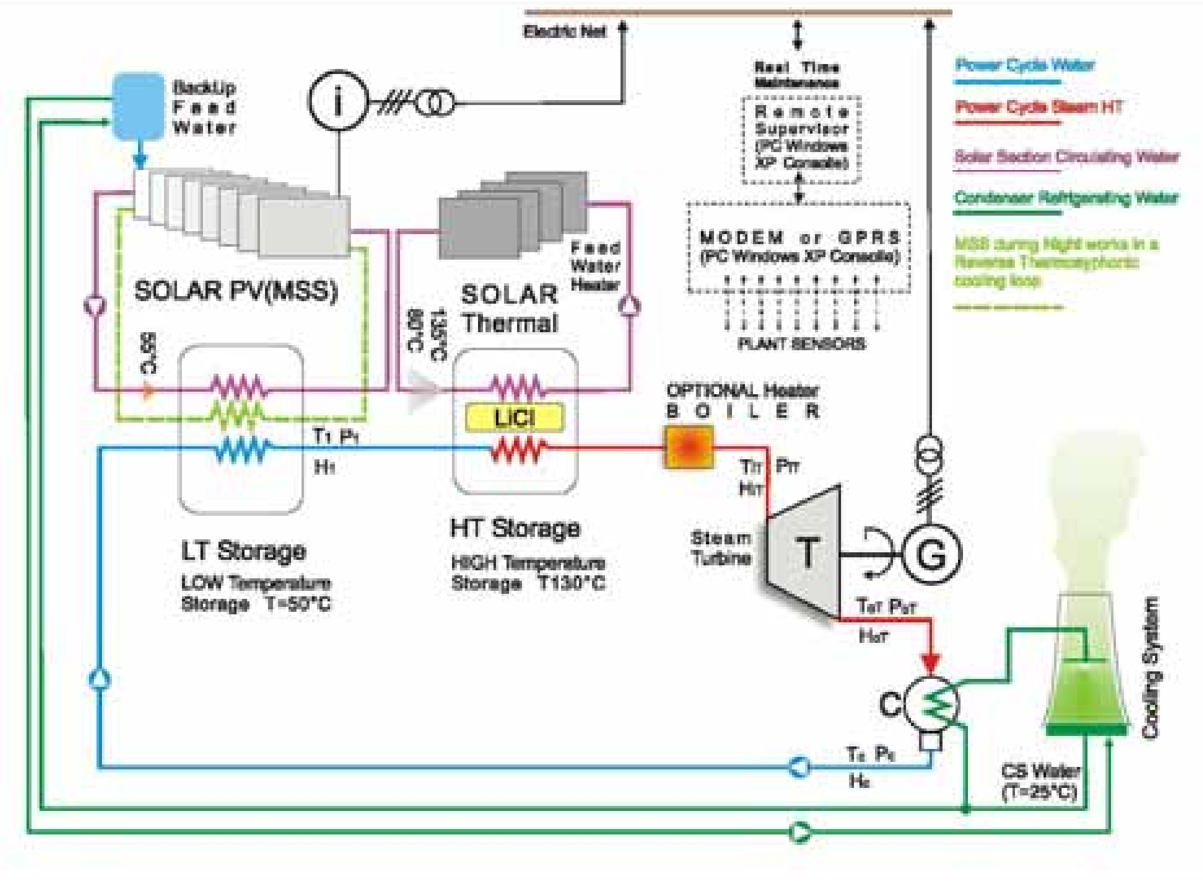
Rankine cycle

In order to get the proper steam quality at the turbine exit (to allow for efficient heat transfer in the condenser and control stability) we chose a turbine inlet pressure of 1.9 bar.

Table 2 - Thermal power plant assumption

Operating fluid	*Water*
Inlet turbine steam pressure	p_I=1.9bar
Turbine adiabatic efficiency	$\eta_{T,ad}$ =85%
Condenser pressure	p_{II}= p_c =0.045 bar

Fig.1



At peak condition, assuming $qi=1kW/m^2$, we will get a peak power from the PV system given by

$P_{PV} = \eta_{e,PV} \cdot q_i \cdot S_{PV} = 9.56\ MWe$

And an heat flux from the PV coolig system (available at a maximum temperature of 55°C) of

$Q_{LT} = q_{r,PV} \cdot S_{PV} = (\eta_{r,PV} \cdot q_i) \cdot S_{PV} = 5.6\ MWt$ (1)

On the other hand, from the thermal solar modules we have

$Q_{HT} = \eta_{r,TS} \cdot q_i \cdot S_{TS} = 3.6\ MWt$ (2)

From the Mollier chart, we can read the turbine inlet and exit enthalpies:

Inlet turbine enthalpy: $h_{it} = 2728\ kJ/kg$

Outlet turbine enthalpy (assuming turbine efficiency = 85%): $h_{ot} = 2312\ kJ/kg$

Outlet turbine steam quality: $x_{ot} = 0.89\ kJ/kg$

The energy required to heat a kg of condensate from the condenser temperature to the LT storage exit temperature is:

$Q^*_1 = c \cdot (T_1 - T_c) = 104$ kJ/kg

while the heat transfer required to raise the same kg of water from 50°C to steam at 1.9 bar, 130°C is

$Q^*_2 = (h_{it} - h_1) = 2512$ kJ/kg

Thus, we need much more heat from the high temperature storage than the lower one. Unfortunately, the ratio between available heat (Eq.1,2) is just the opposite. This means that if we use a single stream of water/steam in the Rankine cycle we would be able to exploit a only a small portion of the LT heat system, given by

$$\frac{Q_{LT,\ usable}}{Q_{LT}} = \frac{Q_{HT}\ Q^*_1}{Q^*_2\ Q_{LT}} = 3\%$$

Two-stream steam turbine

A possible workout is the use of two different steam streams: a large, low pressure one, generating superheated steam at 50°C (with a low heat to electric power efficiency), and a smaller, medium pressure one at 130°C. Both streams will generate power in a single, double entry steam turbine (as in steam turbine in combined cycles). The resulting plant scheme is given in Fig.2.

Fig.2

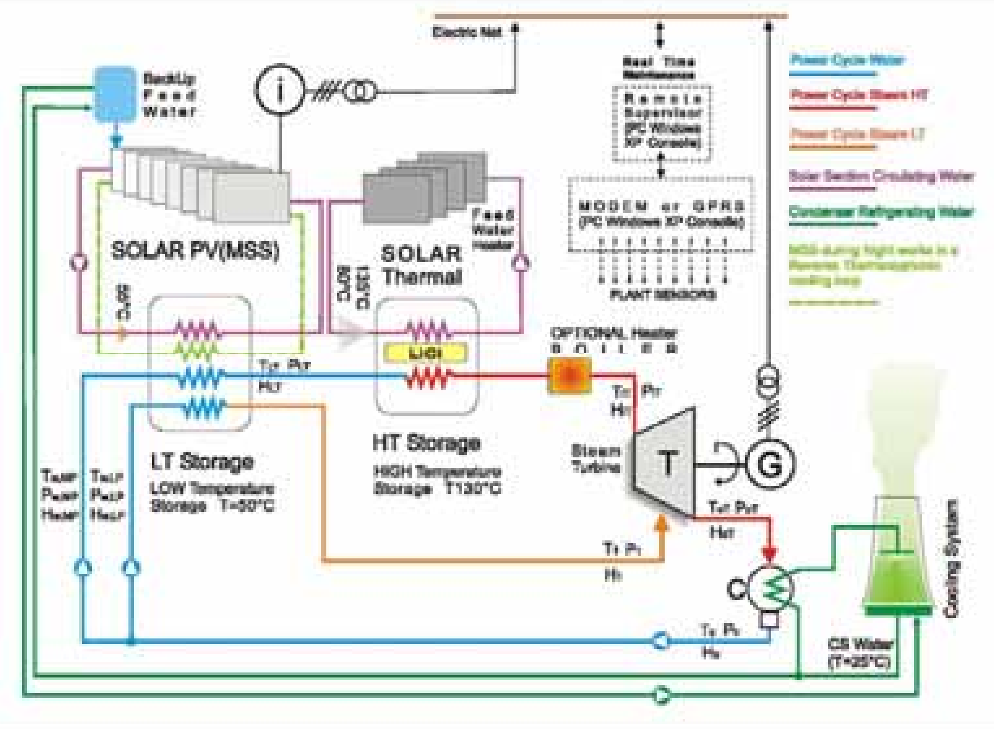
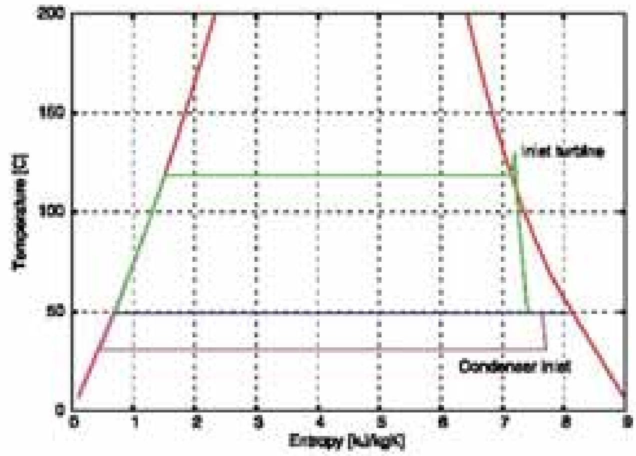


Table 3 - Thermal power enthalpies

	Enthalpy [kJ/kg]	*Temperature [°C]*	*Pressure [bar]*
Medium pressure turbine inlet	h_s=2728	T_s=130	p_s =1.9
Medium pressure feedwater pump exit	$h_{w,MP}$ ≈ 125.8	$T_{w,MP}$ ≈ 30	$p_{w,MP}$ =1.9
Low pressure feedwater pump exit	$h_{w,LP}$ ≈ 125.8	$T_{w,LP}$ ≈ 30	$p_{w,LP}$ =0.12
Low pressure turbine inlet	h_1=2592	T_1=50	p_1=0.12
Turbine exit	h_{st}=2312	T_{st}=30	p_{st}=0.045
Condenser exit	h_c=125.8	T_c=30	p_c= 0.045
High pressure stream water enthapy at LT exit	h_{LT}=209.0	T_{LT}=50	p_{LT} = 0.12

From the Rankine charts, we can reconstruct the evolution of both streams, as in **Table 3**. As a final result, if we want to exploit all of the available heat, we will get, at nominal conditions, 0.656 kWe (e = electric) from the high pressure cycle and 0.717 kWe (e = electric) from the lower pressure stream (at a cycle efficiency of 13%).

The Medium Pressure cycle efficiency is:



$$\eta_{MP} = \frac{h_{3I} - h_{4I}}{h_{3I} - h_{c}} = 18\%$$

The Low Pressure cycle has an efficiency of:

$$\eta_{LP} = \frac{h_{1} - h_{2I}}{h_{1} - h_{c}} = 3\%$$

The global, weighted average Rankine efficiency is:

$$\eta_{Rankine} = \frac{P_{MP} + P_{LP}}{Q_{LT} + Q_{MT}} = 10\%$$

In the end, at nominal conditions we will obtain

Photovoltaic power: $P_{PV} = 0.956\ MWe$

Turbine power: $P_{T} = 1.37\ MWe$

In terms of energy production throughout the year, we must keep in mind that it is not practical to operate the turbine at very low power level. Typically, we're going to operate it for six month, in the hot season. From weather statistics in northern Italy, the average solar energy collected in these six months is 70% of the total. If we assume that ideal storage keeps constant the operating temperatures, also the efficiencies will be constant. Thus, we can compute the yearly energy output under different assumptions. (See **Table 4** for the resume) (*Bottom image: MSS panel design*[2]).

(**Northern Italy**) we could obtain from the PV section
(PV efficiency 12%) :

> Radiation $E_i = 1228\ kWh/year$
> $E_{PV} = 1\ 173\ 800\ kWh$
> and from the turbine:
> $E_T = 800\ 000\ kWh$

With a different location, i.e. **Southern Italy**
(PV efficiency 12%):

> Radiation $E_i = 1700\ kWh/year$
> we could obtain from the PV section:
> $E_{PV} = 1\ 633\ 000\ kWh$
> and from the turbine:
> $E_T = 1\ 124\ 000\ kWh$

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(2) **The Multi Solar (MSS) PV/T/A technology** is the basic element of the Solar Photovoltaic/Thermal Power Station. The MSS is an innovative, patented (PATENT NO 5522944) Solar PV/Thermal/Air System that makes it possible to convert solar energy into thermal energy and electric energy at the same time using a single integrated collector. The Solar thermal/photovoltaic power station will be based on the Multi Solar System in coordination with solar thermal collector array in rows, in order to achieve maximum optimization of the combined system.

With a different location, i.e. **Israel** (PV efficiency 15%):

Radiation *Ei=1800 kWh/year*

PV Efficiency: 15%

Nominal PV power: 1.2MW

PV energy throughout the year: 2160 MWh/year

Turbine energy throughout the year: 1180 MWh/year

Turbine output with a different Tmax, i.e. 150°C :

Tmax=150°C

Tcondenser=30°C

Tintermediate=50°C

PV 8000m^2

Thermal modules 4000m^2

Nominal turbine power=1.42 MW

Energy yearly production from turbine:

In Northern Italy, at 1,228 kWh/year: 850 MWh/year

In Israel, at 1,800 kWh/year: 1250 MWh/year

Table 4- Yearly Energy Output

Plant and Environment Data				**Yearly Energy Output [MWh/y]**	
Geographical Site	**Radiation (kWh/y)**	**PV efficiency**	***Tit max* [°C]**	**PV**	**Turbine**
North Italy (UD)	1,228	12%	130	1,173	1,180
North Italy (UD)	1,228	12%	150	1,173	1,222
Center Italy (Roma)	1,460	12%	130	1,399	1,407
South Italy (Sicily)	1,700	12%	130	1,633	1,642
Israel	1,800	12%	130	1,732	1,735
Israel	1,800	15%	130	2,160	1,735
Israel	1,800	15%	150	2,160	1,798