ENTE PER LE NUOVE TECNOLOGIE, L'ENERGIA E L'AMBIENTE



SOLAR THERMAL ENERGY PRODUCTION:

GUIDELINES AND FUTURE PROGRAMMES OF ENEA.



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1. — General considerations.

1.1. Introduction.

The present report illustrates the Research and Development programmes of ENEA in the field of thermal solar energy and the related strategic choices. This is part of a wider programme aimed at enhancing the large scale exploitation of novel kinds of energy sources in Italy, as a gradual substitution of the conventional uses of fossil fuels.

There is no doubt that the use of new kinds of energy – more durable and less damaging to the environment than burning fossils – will gradually grow in the future. Such progressive change will be driven by (1) the likely inability of fossils to sustain the full extent of the future energetic demand, growing roughly at the rate of + 2.5 %/year world-wide, without large price increases due to progressive scarcity introduced by the demand, and (2) the growing evidence for the triggering of a major climatic change, primarily due to continued use of fossils.

There are apriori *only* two types of primary energy sources which have both the energetic potentials and the durability sufficient to match mankind's future needs: (1) *Nuclear energy (fission and fusion)* and (2) *Sun-derived energy.* The pro and cons of the first are well known; for the latter, ENEA is poised to a very substantial and renovated effort toward the realisation of demonstrative, large scale systems with innovative characteristics.

Further driving elements for this strategic choice are – in addition to the ones mentioned above – the facts that (1) Italy is presently strongly dependent on foreign primary energy supplies [1] and (2) its geographical location, especially the Southern tip of Italy, is rather favourable to the exploitation of the direct sun light [2].

Solar energy can be used either directly (heat, PV, etc.) or indirectly, through its effects on generating wind, rain (hydro-) or vegetation growth (biomass). But until now and with the exception of conventional hydro- and traditional wood-burning (mainly in developing countries), *sun-related energies have represented only a very tiny fraction of fossil derived energies*. In order to reverse this situation, solar energy must become more cost-competitive and more responsive to the actual demands of the market. We believe that such a goal can be achieved only with the development of a number of new technologies, which are an absolutely crucial premise to a more widespread use of solar energy.



In the vast majority of conventional uses of fossil fuels, high temperature heat is produced in a highly concentrated form, through the combustion of solid, liquid or gaseous fuels inside a burner¹. The closest solar analogue process is then direct heating with a highly concentrated solar light directed on a "heat collector".

Under ordinary but favourable conditions, direct solar light has a peak power density of about $dW/dS \approx 0.1 \ Watt \ cm^{-2}$, sufficient to produce warm water or house heating, but largely insufficient for generation of higher temperatures. Optical concentrators, however, permit to increase this light density by factors 100 ÷ 3000 times, thus producing an ultimate power density in the focal waste of the order of $dW/dS \approx 10 \div 300 \ Watt \ cm^{-2}$, which is quite comparable with the one generated by a traditional flame.

The method of solar concentration has been preferentially selected by ENEA, since it offers the possibility of extending many existing industrial technologies (like for instance thermal electricity generation, gasification of carbonaceous materials to form synthesis gas, thermal cracking of low hydrocarbons to produce important basic materials, endothermic industrial reactions, etc.) to the solar option and holds the best promises for low cost, in view of the simplicity of the collection method for the solar light, which is by now at least 2000 years old (Archimedes).

¹ In many other applications, the fossil has also specific chemical functions, beyond the simple combustion with air. These applications do not have an immediate analogue in the solar case.

1.2. How much energy from the sun?

The yearly averaged heat power produced per unit area normal to the Sun's direction (perfect focussing) $\overline{W_o}$ is given in Figure 1. In the best conditions of the "Sun belt", it amounts to about $\overline{W_o} \ge 280 \ Watt \ m^{-2}$. A more conservative value, which greatly extends the potentially useful land could be $\overline{W_o} \ge 200 \ Watt \ m^{-2}$. As already pointed out, the concentrator technology allows to focus such power on a small spot, thus producing a high temperature heat which may be made rather similar in its effects to the one produced by a flame of a fossil fuel. With appropriate arrangements, discussed further on in this report, one should be able to collect the direct solar radiation incident on the collectors plane with an efficiency $\varepsilon_{thermal} = 2/3$ and store for further use, solar heat with a yearly yield per unit area $E_{eff} = \varepsilon_{thermal} \ \varepsilon_{angle} \ \overline{W_o} H \approx (2/3) \times 0.95 \times 280 \times 8.76 \times 10^3 = 1553 \ [kWatt \ h \ m^{-2}] = 5.59 \ GJ \ m^{-2}$, where $\varepsilon_{angle} = 0.95$ is the yearly averaged ratio between the solar radiation on the collector plane and the direct normal solar radiation² and $H = 8.76 \times 10^3$ are the number of hours in a year. For less favourable locations where $\overline{W_o} = 200 \ Watt \ m^{-2}, E_{eff} = 3.79 \ GJ \ m^{-2}$.

As a comparison, a barrel of crude oil (BOL), used with 100% efficiency, generates nominally 5.71 GJ. Therefore each square meter of solar collector in optimal location may deliver yearly about the energetic equivalent of one barrel of crude oil, for which we may take an indicative value of ≈ 24 \$US. The cost thus saved would allow an initial capital investment (principal value) of ≈ 100 \$US, if it is repaid for instance in five years³ at a yearly compounded current interest rate. This sets for a financially competitive installation of solar concentrators an order of magnitude of the capital cost of collectors of about ≈ 100 \$US/m². Of course this is only a very rough estimate since it takes into account only the crude oil supply. A more precise analysis taking into account all factors is obviously necessary and it will be discussed further on. However it is worth setting an order of magnitude of the cost at which solar thermal may compete with fossils already at this stage.

The measured direct sun's energy density (Watt/m²), as a function of the day of the year for two typical locations, Albuquerque, USA and Gela, Italy is displayed in Figure 2. The daily behaviour has also been expanded for a chosen

² \mathcal{E}_{angle} is related to the yearly averaged incidence angle of the solar radiation onto the collectors plane. It depends from several factors: the adopted concentration system, the latitude angle, the collectors orientation and the shadows projected by the adjacent collectors. For a single axis concentrating system aligned along the North-South orientation at low latitude angle its value is 0.95.

³ The operational lifetime of a properly designed solar thermal plant should be of the order of at least 30 years



ten days period, in order to show the detailed variation over the day. The averaged values $\overline{W_o}$ are in good agreement with Figure 1. Note that the yield at Gela, $\overline{W_o} \approx 200 \text{ Watt/m}^2$ is lower than the one in Albuquerque, $\overline{W_o} \approx 300 \text{ Watt/m}^2$ because of the more adverse winter, while during summer are essentially the same.

1.3. Critical problems with solar thermal energy.

The ENEA R & D strategy is specifically directed on solving several, critical problems which have hindered a more widespread use of solar energy. Indeed, in order to ensure more significant future uses, for instance at a level comparable to the one of today's fossils, we must overcome a number of major hurdles, which are briefly summarised below.

i) One has to overcome the *time variability effects* of the source (from the passage of a single cloud over the installation, to diurnal and seasonal variations, see Figure 2). In order to be competitive, solar

energy must be available whenever needed, overcoming its intrinsic variability. A major thrust in the ENEA solar programme will be dedicated in ensuring "dispatchability" as a key feature of any mature energy producing method. As well known, solar energy on earth is an intermittent source which exhibits, by its own nature, time Its discontinuities which are substantial and often unpredictable. effective utilisation for human activities requires a suitable *energy* storage system, transforming the directly delivered, but intermittent sunshine energy into a continuous energy flow adapted to the specific application. There are several types of discontinuities displayed in Figure 2 and which can be roughly divided in four broad classes: (i) accidental, unpredictable, generally short term, interruptions of direct solar intensity due to clouds movements, during an otherwise productive day; (ii) the night-time idling period; (iii) bad days, due to adverse weather conditions; (iv) seasonal variations, related to the yearly cycle. These different classes of discontinuities correspond to vastly different storage times. While variations of types i) and ii) may be completely smoothed out by an energy storage of a few tens of hours, type iii) may require several days of storage, depending on the location of the installation and finally type iv) are hard to compensate with storage and they should be taken into account in the exploitation schedule as an inevitable characteristic of the cyclic nature of the solar power generated⁴.

The most promising form of storage and our preferred choice appears to be the so-called "thermal storage", namely a method in which a suitable medium, either liquid or solid - well insulated against thermal losses – is kept for the required time at the high temperature which the solar energy has generated. It is worth comparing this "thermal" stored energy density with energy "chemically" stored in the form of fuel and extracted by combustion. Evidently for the latter case a much larger "stored" energy density is expected. While thermal storage is based on changes of the mean kinetic energy due to thermal motion – namely $k\Delta T/2 \approx 10^{-2} eV$, (k is the Boltzmann constant) for each elementary molecular degree of freedom chemical reactions produce a few eV's for each elementary process. On the other hand, thermal storage is perfectly reversible, very simple, cheap, highly efficient (≈99%) [3] and perfectly matched to the nature of the solar energy source. Chemical storage by conversion of solar energy into chemical energy, followed by subsequent

⁴ We remark that this variation becomes of less importance at small latitudes around the equator.

combustion, is evidently also possible, but it is less efficient, more costly and requires a substantial amount of additional hardware. Other forms of energy storage have been compared with thermal storage and all resulted more expensive and complicated.

Two different types of thermal energy storage will be simultaneously developed under the ENEA programme, namely (i) a *molten salt storage* in which circulating liquid is stored at about 550 °C and (ii) *packed beds of small solid pebbles* or otherwise shaped solid materials, heated with gas circulation, which operate at higher temperatures, up to about ≥ 900 °C.

ii) There is also the need to deliver solar energy – generally produced in remote and desert regions - to users in other areas where land is more precious or the sunshine is not so plentiful, with an adequate long distance transportation. A key feature of the solar energy is the fact that it is most suited for locations of otherwise desert, cheap land, in good sunlight exposure conditions (the "Sun Belt", see Figure 1). On the other hand energy is needed generally far away from the production point, where population is resident and where the cost of land, necessarily much higher because in demand, is not economically suited for these large scale installations. In these locations, in many instances, the solar resource is not optimal. Therefore when choosing the technological options to harness solar energy one must inevitably take also into consideration the choice of the related "energy carrier".

Amongst them, two emerge with the unique property of producing "zero emissions" both at production and at utilisation points, namely (i) *electricity* and (ii) *hydrogen* for instance from water splitting, as substitute for natural gas. Both forms of energy delivery from solar thermal energy, are included in the ENEA programme.

Electricity is becoming the highly preferred form of energy for a growing number of applications, as shown in Figure 3. It is plausible to expect that, at least in the most developed countries, more than 50 % of all energy consumption will soon be in this form. However transportation of electricity, though it is currently performed on medium distances, may be too costly and/or inefficient over very long distances, as it would be necessary if energy, massively produced in the "Sun Belt", should be widely distributed in the areas with largest human activity. Indeed, at present, most of the energy transported on a planetary scale is in the form of chemical,



combustion energy of fossils, either solid, liquid or gaseous. In particular the use of natural gas is rapidly growing.

The introduction of *Hydrogen* (H₂) as energy carrier in substitution to natural gas requires no major technological breakthroughs. H₂ is a remarkable energy carrier. It is technically feasible to replace oil and natural gas with H₂ in virtually all present uses. H₂ can be stored, transported and delivered using technologies which are similar to the ones widely used for natural gas.

As pointed out, natural gas, contrary to electricity can be transported over distances of several thousand kilometres at a modest cost: $2 \div 3$ \$US/GJ for a typical distance of 1500 km over land⁵. H₂ has a much smaller density than methane (0.0899 vs. 0.714 g/litre n.t.p.) and a combustion energy per unit volume which is only 1/3 of the one of methane (12.76 vs. 39.7 kJ/litre n.t.p.). The diffusion is larger by a factor almost three, which implies tighter seals. But it will flow more easily through a pipe, about a factor 2.8 faster. A pipeline designed for natural gas will transport H₂ at the same pressure, but with only 80% of the energy flow. In general [4] one can expect that the cost of transmission for unit energy of H₂ will be about 50% higher than for

⁵ A large energy flow (10 to 20 GWatt) can be realized with pipes of reasonable diameter of 1.4 m and pressures of about 80 kg/cm².

natural gas.

Studies on relative safety of H_2 , natural gas and gasoline have concluded that no one fuel is inherently safer than the others in every respect, but all three fuels have been used safely [5]. H_2 has a leak rate which is 2.8 times the one of methane, but comparable to the one of gasoline. All three fuels ignite easily, but hazard persists longest with gasoline, then methane and H_2 . Toxicity of gases is negligible, in contrast with gasoline. Hydrogen-rich gases have been used for home heating and cooking for more than a century. "Town Gas" is a mixture of approximately one half H_2 and one half CO and it has been generally used in most developed countries before natural gas became widely available.

Therefore H_2 is an ideal substitute for natural gas and its production in industrial quantities with solar energy is an attractive alternative for the future, with the added advantage of zero emissions. Evidently the cost at production must be competitive with the one of natural gas, which is presently of the order of $4 \div 5$ \$US/GJ. Mixtures of H_2 and of natural gas may be introduced as a first step.

iii) Finally, solar energy must be produced at a competitive cost. In order to become an alternative, solar energy must have a cost comparable to the one of fossils (the "best" energy is the cheapest energy). As already pointed out, in optimal conditions solar thermal technology may produce a yearly energy $E_{eff} = 5.89 \ GJ \ m^{-2}$ in the form of high quality, stored heat. In order to produce such a quality heat for instance at the reasonably competitive price of 5 \$US/GJ, the yearly over-all costs of the part of the installation related to the harnessing of solar heat (running (O & M) costs plus amortisation of the invested capital) should not exceed 5.89 x 5 \approx 30 \$US/m². Presently the current cost of thermal solar collectors [6] is substantially higher than what permitted with such potential revenue figure. Therefore we must achieve a very substantial cost reduction with a robust, but cheaper collector technology. The cost of the produced electricity, for a given cost of heat, is independent of the technology (fossil vs. solar heat), since the same type of standard equipment can be used in either case for electricity production.

1.4. Lines of intervention and basic choices.

On the basis of the previous considerations, the ENEA R&D programme will follow two main strategic lines which are pursued in parallel:

i) Medium temperature heat production (about 550 °C) and storage, primarily intended for electricity production. This choice of temperature is a compromise between thermodynamic efficiency and mature designs for the collector and the thermal storage. A large size energetic storage is of primary importance in order to ensure a good dispatchability of the plant. Such a thermal storage will consist of a pair of thermally insulated tanks of molten salt⁶ (nitrate) with the approximate temperatures of 565 °C and 290 °C, corresponding to ΔT = 275 °C and a storage capacity per unit volume typically of $dE/dV = 0.731 \ GJ \ m^{-3}$. The solar heater feeds the hot tank, starting from the liquid from the cold one. The peak solar power during the daytime is transformed in a continuous supply of high quality heat around the clock.

In order to be applicable to the proposed extended storage, collector's temperature must be upgraded substantially, of as much as about +200 °C with respect to the already mature generation of parabolic troughs, ordinarily designed for a delivery temperature of 390 °C. As well known, two concentration schemes are apriori possible:

- One dimensional concentrator, with cylindrical, parabolic concentrators acting along a tube with solar full angular collection aperture $\Delta \theta$, as seen from the focal point.
- *Two dimensional concentrator*, with the collector in the focal point of a circular revolution parabola and a solar full angular collection solid angle $\Delta\Omega$, as seen from the focal point. From simple geometry considerations, $\Delta\Omega = \pi/4(\Delta\theta)^2$, where $\Delta\theta$ is the full collection aperture, as seen from the focal point.

Let $\Delta \sigma = 9.3 \times 10^{-3}$ rad be the full angular aperture of the sun in the sky. The concentrator starting from an initial solar power density $(dW/ds)_{sun} \approx 0.1$ Watt/cm² will produce in the focal point at best a surface power density $(dW/ds)_{focus} = \Gamma(dW/ds)_{sun}$, where Γ is the concentration factor. This factor, by the Liouiville theorem, is $\Gamma = \Delta \sigma / \Delta \theta$ and $\Gamma = (\Delta \sigma)^2 / \Delta \Omega = 4 / \pi (\Delta \sigma / \Delta \theta)^2$ respectively for cases 1) and 2) above. Therefore for a cylindrical geometry $\Gamma \approx 50 \div 240$, while for a parabolic geometry, $\Gamma \approx 1000 \div 10000$.

The added advantages of a two-dimensional focussing 2), capable of

⁶ Mineral oil used in conventional SEGS (Solar Electric Generation Station) has also serious problems of environmental impact, since it is spontaneously flammable at the operating temperature.

attaining higher temperatures, should not underestimated. However – if materialised in the well known Solar Tower approach, in which a large number of mirrors focus the solar energy onto a high tower located at a considerable distance – it will demand much more stringent requirements for mechanical tolerances and flatness of the mirrors and of the orienting system, which are not without additional costs, a crucial parameter for the success of the programme. We have finally retained the more conservative alternative 1), provided adequate feasibility is confirmed by our on going R&D work. Amongst the main goals of this programme, we must (1) extend the linear parabolic collection technology to a nominal temperature as high as 565 °C and (2) introduce a new type of collecting mirrors with the lowest possible unit cost.

The linear parabolic collectors are already a relatively mature technology. However in view of the substantial upgrades from the existing technology, the programme has been split in two progressive phases: (1) a first demonstration with an installation of 4 MWatt_e to be realised in the new ENEA-Advanced Solar Laboratory (Laboratorio Solare Avanzato, LASA) presumably near Latina and (2) a subsequent, industrial scale modular installation made of one or more modules with 40 MWatt_e of electric energy – delivered around the clock (full day) and with a yearly availability $\geq 80 \%$ – to be realised on a new "industrial" site in the South of Italy.

ii) High temperature (≈ 850 °C) heat collection and direct hydrogen production. The thermal storage described in the previous paragraphs is suited for medium temperatures (≈ 550 °C), at which the heat storage liquid is chemically stable. On the other hand, the solar collection with parabolic concentrators (concentration factors Γ in excess to 1000 fold) can achieve substantially higher temperatures which are of considerable interest, since they permit both a higher thermo-dynamical efficiency in electricity production and other applications, like for instance hydrogen from the dissociation of water.

No H₂ natural sources exist to the appropriate scale and H₂ must be produced from other energy sources: like electricity it is purely an energy carrier. Direct thermal dissociation of water requires temperatures in excess of 2100 °C. Therefore several different alternative methods have been developed [7], in which dissociation of water is the end product of a more complicated chain of chemical

reactions⁷, with the advantage of a much lower operating maximum temperature, typically of the order of 850 °C.

 H_2 production by thermo-chemical water-splitting is a purely chemical process that accomplishes the decomposition of water into H_2 and oxygen using only heat or, in the case of a hybrid thermo-chemical process, by a combination of heat and electrolysis.

Thermo-chemical water-splitting cycles have been known for the past 35 years. They were extensively studied in the late 70s and early 80s [8, 9, 10, 11 and 12], in order to define an economically feasible process for the production of hydrogen by nuclear means, using an advanced high-temperature nuclear reactor as the energy source, but they have been essentially neglected in the past 10 years. While there is no question about the technical feasibility and the potential for high efficiency, cycles with proven low cost and high efficiency have yet to be developed commercially. Over one hundred cycles have been proposed, but substantial research has been executed on only a few.

The final ENEA scheme for water dissociation is still subject of further investigations, since several processes exist which could perform such a transformation in general with about 50% efficiency and at an attractive cost. Particularly interesting is the so called process UT-3 [13], developed by the University of Tokyo, which will be taken as reference design. In this process, high temperature heat is collected by independent parabolic collectors and transported by gas to a thermal storage made of packed beds of small solid pebbles or otherwise shaped solid materials which are heated with gas circulation. Depending on the temperature, several different packed bed materials can be devised, like for instance alumina, ceramic, crushed rock or metals. These pebbles are generally contained in a sealed and thermally insulated vessel, with gas entrances at the top and the bottom. During charging process hot gas from the solar receiver flows from top to bottom, through the packed bed, transferring heat to the bed. A stratified condition is realised, with a hot zone at the top, a thermocline zone in the middle and a cold zone at the bottom. Charging is complete when the thermocline region reaches the bottom of the vessel. During the discharging process, relatively cold gas flows from bottom to top and reaches almost the same temperature of the hot zone of the bed. The discharge is

⁷ Almost 800 literature references were located [8] which pertain to thermo-chemical production of hydrogen from water and over 100 thermo-chemical water-splitting cycles were examined. Using defined criteria and quantifiable metrics, few cycles may be selected for more detailed study.

considered to be complete when the outgoing gas temperature drops by a specified value, for instance 30 °C. The thermal capacity of these devices is generally comparable to the one of the molten salt. For instance a specific design based on Al₂O₃ ceramic pebbles has at 900 °C a typical thermal capacity $dE/dV = 0.6 GJ m^{-3}$ [14].

The development of solar hydrogen production has necessarily a much longer time scale. Laboratory tests of the chosen chemical process must be performed before launching a solar driven prototype of several MWatt, to be constructed probably at the ENEA-Advanced Solar Laboratory LASA.

1.5. The energy storage.

As already pointed out, an extended energy storage is one of the main strategic choices of the ENEA programme, both for industrial heat and for hydrogen production. We believe that in this way the intrinsic variability of solar energy can be matched with the steady availability requirement of any industrially based mature application. The method adopted is based on a simple, repetitive heating/cooling cycle of an appropriate (liquid or gas) medium circulating between two, well thermally insulated, equal volumes A and B, respectively at "high" temperature T_A and at "low" temperature T_B . In order to keep T_A to the prescribed value, the flow is adjusted as a function of the solar flux. Neglecting heat losses, the thermal energy stored for unit mass is $\Delta E = [H_a(T_A) - H_a(T_B)] \approx c_n (T_A - T_B)$, where H_a is the specific enthalpy. If no significant phase or chemical transition occurs in the temperature interval, in a good approximation $c_p \approx const$, and ΔE is simply proportional to the temperature difference.

It is interesting to compare the performances of the different industrial methods for energy storage. As discussed in more detail further on, the proposed thermal storage capacity per unit volume for molten salt (mixture 60% NaNO₃-40% KNO₃ at 550 °C, specific heat capacity $c_p = 1529$ J/kg K and density d = 1739 Kg/m³) [15 and 16] is typically dE/dV = 0.731 GJ m^{-3} . For Al₂O₃ ceramic pebbles at 900 °C we have about dE/dV = 0.6 GJ m^{-3} . For instance, the stored energy of molten salt is about the same as the one obtained by the combustion of an equal volume of natural gas compressed at p = 18.4 bar or hydrogen gas at the pressure of p =57.3 bar (25 °C).

The complexities and the extra costs of building and operating such a gaseous storage are considerable (pressure, chemistry, and so on). In addition the energetic efficiency of the transformations is substantially smaller than unity (≤ 50 % for typical installation, which means doubling the size of the solar field



for a given ultimate performance). Therefore short and medium term chemical storage in the gaseous form is not competitive with thermal storage. *We consider* H_2 production as an attractive energy carrier, not as a local energy storage.

In Figure 4 we compare storage volumes for equal stored energy but different methods. A much higher energy concentration is offered by the liquid fuels⁸, using the heat of combustion. Combustion heat densities for gasoline (similar values for fuel oil) and for methanol are dE/dV = 31.5 GJ m^{-3} and dE/dV = 14.4 GJ m^{-3} respectively. Comparing these values with the molten salt (e.g. dE/dV = 0.731 GJ m^{-3}) for the same stored energy, the linear (volume) dimensions of a thermal storage tank are 3.50 (43.1) times larger than a gasoline tank and 2.70 (19.7) times larger than a methanol tank.

In order to exemplify the "grand substitution" of fossil energy to thermal solar energy we refer to the conceptual schematic of an idealised installation as shown in Figure 5, where the example of a standard electricity generation by high temperature steam has been chosen.

In the conventional scenario of an oil-fired installation, the heat for the steam is generated by the combustion of mineral oil, stored in a reservoir, of sufficient capacity to allow operation between refuelling. In the solar driven scheme the heat to produce the steam to run the turbine is provided with the help of an appropriate heat exchanger/steam generator by the hot liquid stored in a thermally insulated tank. The liquid flows from the hot tank, through the heat exchanger to a second tank, where is recovered in order to be heated again

⁸ Liquid hydrogen is likely to be excluded in practice because of the technical complications of liquefaction.



in the solar field. An energy storage with sufficient capacity must be provided in order to compensate fully for (daily) variations and short term interruptions of solar flux.

Let us compare the operation (i) the conventional oil-fired and (ii) the thermal solar installation (with molten salt storage), both intended to supply a given process requiring a given, high quality heat. An oil-fired installation will use an adequate fuel storage tank, periodically refuelled. In this case, the energy storage is evidently the fuel tank. The solar driven equivalent installation will extract energy from the hot molten salt. The ultimate thermal capacity of each of the two storages is evidently proportional to the required maximum duration of storage. While in the case (i) it should be of the order of the refuelling periodicity, typically several months, in the case (ii) the storage time is defined by the daily cycle, eventually extended in order to provide extra energy in the occurrence one or more days with low sun yield.

Therefore the amount of energy to be stored thermally for (ii) will be far less than the chemical storage (i), with consequent reduction of its size, with respect to the limiting cases of Figure 4.

There is no major limitation of the time duration of a thermal storage, due to the heat losses of the container. A considerable industrial experience for instance with cryogenic liquid storage, primarily liquid natural gas, has shown that it is possible to reduce such heat losses to a very low level, hence increasing the decay time constant τ_o of the storage installation, characterising the relative energy loss dE/E after the time dt by the expression $dE/E = dt/\tau_o$.

The storage capacity to heat losses, occurring at the walls, ratio improves with larger volumes, since the energy stored goes like the volume⁹ ($\propto L^3$) while heat losses vary like the surface ($\propto L^2$). In ordinary conditions and for few days of heat retention, the addition of the thermal storage should introduce an energy loss of the order of 1% or less. Hence the fractional heat loss improves roughly like $\propto L^2/L^3 \propto 1/L$.

An approximate formula for the daily temperature loss of a practical, full storage, as discussed further on is $dT/dt \approx 26.3/L(m)$ °*C* day^{-1} . For instance, in the case of a tank with L = 30 m, the natural decay should be as small as dT ≈ 1 °C/day with the energy loss time constant τ_a approaching one year.

A modular storage capacity of 3000 MWatth has been chosen for the reference design of section 4.5. Such a tank would contain 14770 m³ of liquid and have a thermal storage capacity of 10800 GJoule, e.g. the equivalent of 342 m³ of fuel-oil. With a typical conversion efficiency into electricity of 0.41, such a storage could maintain alone a continuous electricity production of 40 MWatt_e during 3000 x 0.41/40 = $30.7 \ hours^{10}$. In the case of this plant, a storage of chosen dimensions can smooth out realistically all major fluctuations over a period in excess of one week.

Thermal storage may represent a large volume but non necessarily a large cost, since the price of such a natural salt, widely used in agriculture, is very low and a part of the initial capital investment.

⁹ Let L be the linear dimension (L = diameter = height) of a cylindrical storage tank.

¹⁰ The same volume of 14770 m³ of fuel oil will operate the plant for 55 days. It is unrealistic to assume that oil refueling in a standard power plant could occur with a shorter frequency. Hence the HSU and a perspective oil tank for a plant of this power are quite comparable !

The environmental impact of such a large amount of nitrate salt is very benign. Alkaline nitrates are used in agriculture as fertiliser and they are available in nature in large quantities (Nitrate from Chile). Alternatively they can be easily synthesised. They are highly soluble in water. An accidental spill of nitrate should therefore have roughly the same impact as a fertiliser in a field.

It should also be noted that an accidental leak would involve the cooling of the nitrate below the solidification point of about 240 °C, thus effectively hindering any prolonged loss. The storage tank should be normally installed underground where solidification will have in general a powerful sealing effect.

1.6. Other storage methods?

In order to further assess the advantages of the method based on the thermal storage of solar energy in the form of high quality heat (HQH) we shall compare it with other known methods.

It is of course also possible to produce immediately electricity, which is then stored in some convenient form and later regenerated as electric energy. A vast literature exist on many different methods. When comparing for instance with the molten salt storage, one has to recall that the energy specific storage capacity is $dE/dV = 0.731 GJ m^{-3}$. Since the electric energy may be produced with an efficiency $\eta_{conv} \leq 0.45$, a more appropriate reference is $dE/dV = 0.329 GJ m^{-3}$. As we shall see, all these methods have substantial drawbacks with respect to the molten salt technology.

i) Pumped hydropower. Pumped hydro has been vastly in use since 1929, making it the oldest of the central station energy storage technologies. In fact, until 1970 it was the only commercially available storage option for generation applications. Conventional pumped hydro facilities consist of two large reservoirs, one is located at base level and the other is situated at a different elevation. Water is pumped to the upper reservoir where it can be stored as potential energy. Upon demand, water is released back into the lower reservoir, passing through hydraulic turbines which generate electrical power¹¹. The round trip efficiency of the process is about 70 % [17]. Additional barriers to the use of this storage technology beside high construction costs, include long lead times as well as the

¹¹ In order to reach the value $dE/dV = dE/dm = 0.329 \ GJ \ m^{-3}$ water must be lifted in the gravitational field by an amount $\Delta h = (dE/dm)/g = 3.29 \times 10^5/9.81 = 3.35 \times 10^4 m$, or over 33 km. Assuming a realistic value h = 200 m, the water volume is about 150 times the volume of the stored molten salt. This can be done but it is costly (see Table 1)

geographic, geologic and environmental constraints associated with the reservoir design. An attractive possibility could be the development of underground facilities.

- ii) Compressed Air Energy Storage (CAES). CAES plants use electric energy to compress and store air in an air-tight underground storage cavern. Upon demand, stored air is released from the cavern through a turbine to create electrical energy¹². Barriers include long lead times as well as the geographic, geologic and environmental constraints associated with the safety of the reservoir design.
- iii) Super-conducting Magnetic Energy Storage (SMES). A SMES system stores energy in the magnetic field created by the flow of direct current in a coil of super-conducting material. To maintain a superconducting state, it is immersed in liquid helium in a vacuuminsulated cryostat. New superconductors commence to appear on the market which may operate at liquid nitrogen temperature. It can be easily shown that for the same stored energy and volume the pressure on the coil is equal to the one of the gas to the walls in a CAES storage¹³. Therefore in this respect, magnetic storage offers no distinctive advantage with respect to the compressed gas.
- iv) *Batteries*. In recent years, much of the focus in the development of electric energy storage technology has been centred on battery storage devices. There are currently a wide variety of batteries available commercially and many more in the design phase. The first commercially available battery was the flooded lead-acid battery which was used for fixed, centralised applications. The valve-regulated lead-acid (VRLA) battery is the latest commercially available option. The VRLA battery is low-maintenance, spill- and leak-proof, and relatively compact. Zinc/bromine is a newer battery storage technology that has not yet reached the commercial market. Other lithium-based batteries are under development.

¹² In the perfect gas approximation, the energy stored in a unit volume is $dE/dV = p^{(1)} \log(p^{(1)}/p^{(2)}) = 4.6 p^{(1)}$ for $p^{(1)} = 100 p^{(2)}$. Therefore $dE/dV = 0.329 \ GJ \ m^{-3}$ corresponds to 7.14 × 10⁷ Pascal = 714 bar. At a more realistic pressure of 100 bar we need an underground volume which is 7 times the one of the molten salt. The pressure force on the walls will of course be enormous, 1000 t/m².

¹³ The stored energy in unit volume of field B is $dE/dV = B^2/2\mu_o = 3.68 \times 10^5 B^2 (Tesla)$. The reference value $dE/dV = 0.329 GJ m^{-3}$ corresponds to an enormous field B = 29.8 Tesla. For the more reasonable value of B = 5 Tesla, the magnetic field volume is then 35 times the molten salt volume. Forces on the toroidal coil are a main technical problem.

Table 1 summarises the key features of each energy storage system[18]. Cost estimates are for complete systems with power conditioning subsystems (PCS), controls, ventilation and cooling, facility, and balance of plant.

In conclusion, thermal energy accumulation — in which the energy from the sun is transferred to heat up to high temperature an appropriate, thermally insulated bulk material — appears to be by far the best method.

	Type of storage	Cost for a 200 MW plant (\$/kWh _{electric})	Operation Lifetime (years)	Storage efficiency (%)	Operating temperature (C°)
Molten-Salt	HQH	30	30	99	567
Synthetic-Oil	HQH	200	30	95	390
Pumped hydro	ELE	500 to 1600	30	50	N/A
Compressed air	ELE		30	60	N/A
Superconducting	ELE	> 1,000	30	90	cryogenic
Battery Storage	ELE	500 to 800	5 to 10	76	N/A

Table 1. Comparison of solar-energy storage systems.

2. – Collection of solar heat with linear parabolic trough.

2.1. Introduction.

The main guidelines of this programme, as already mentioned, and which differentiate this programme from standard solar installations are:

- i) A new mechanical design of the parabolic mirrors in order to reduce substantially the cost. The supporting material is curved Aluminium Honeycomb, with steel skins and a thin mirror layer in the inner side.
- ii) The surface coating of heat collecting tube has been upgraded, in order to ensure a reasonable radiative heat losses at an operating temperature in excess of 550 °C. The molten salt is circulated directly inside the heat collecting tubes.
- iii) The heat storage is performed by storage of circulating molten salt in an appropriate reservoir of sufficient capacity in order to provide a conservative heat reserve to cope with daily as well other discontinuities. The storage capacity will be considerably enhanced with respect to existing installations, both SEGS and Solar Towers [19].

As already discussed, the simplest and most economical way is the one of accumulating in a thermally insulated environment the very same liquid medium carrying the heat between the solar field and the energy generating plant, in the form of a *molten nitrate salt*. The storage technology is at least an order of magnitude cheaper than all other methods considered, it is 99% efficient and it has little or no environmental impact or hazard, the salt being a material available in nature and widely used as fertiliser in agriculture.

Dispatchability is a key feature of any mature energy producing method. On the other hand, solar energy exhibits, by its own nature, time discontinuities which are substantial and often unpredictable. An adequate "daily storage" has to be considered as a necessity for any practical, stand alone, thermo-electric solar installation in order to smooth out the accidental, generally short term interruptions due to clouds movements and to provide the required power availability around the clock, starting from a limited solar exposure from dawn until dusk. Therefore the technology of the solar collectors must be fully matched to the requirements of the storage system, which is the "heart" of the installation. The properties of this heat carrying liquid determine directly the highest temperature from the solar field, in order to avoid decomposition (≈ 550 °C) and the minimum temperature (≈ 290 °C), which should be adequately far from the freezing point. In order to reduce costs and simplify the operation it is also assumed that the molten salt will circulate directly in the solar collectors.

2.2. The solar collectors.

Reflecting panels and sustaining structures must convoy the maximum incident energy onto the tubular heat collecting unit (HTU). Stresses, generated during operating conditions, mainly by wind, must not affect performance of the optics. In order to ensure a constant optical efficiency, flexural and torque distortions (caused by bending and twisting moments) must result in changes of the reflection angle ≤ 1 mrad, which is the angular aperture of direct sunlight. In addition, induced stresses even in extreme circumstances (high winds), must not exceed the breaking load of materials, particularly of the mirror surfaces, which, incidentally, must be easily replaceable and adjustable on site.

The reflecting profile of the existing and most advanced Solar Electric Generation Stations (SEGS) installations (LS3), is made of parabolically shaped 4 mm thick mirrors, having a focal length of 166 cm and a maximum lateral span 576 cm. It has been shown that the glass surface of these mirrors is long lasting and that it can be easily cleaned. There is no long term degradation of the reflectivity property; cleaning can easily restore full reflectivity to ten years old mirrors. However they remain relatively fragile and under extreme circumstances they may even break [20], for instance under vibrations induced by wind turbulence, wind pressure loads or by contrasting interactions with the steel supporting structure due to thermal stresses.

The raw cost of these mirrors is $52 \div 60 \text{ US/m^2}$, to which it is necessary to add an additional, about equal cost for assembling and aligning them on site. The major contribution to the mechanical stability of the assembly is ensured by the independent supporting structure, which is therefore also expensive. The over-all cost of the LS3 type mirror assembly exceeds 200 US/m^2.

We recall the considerations of paragraph 1.2, where it is pointed out that, in order to keep a competitive edge with respect to fossil, the cost of the full mirror assembly should not exceed 100 \$US/m². Low-cost/high-performance solar collectors are therefore needed to make solar thermal power competitive with other fuels. Alternative, cheaper and more robust design is a key feature of the ENEA thermal solar programme.

Although a variety of different reflective materials have been developed for sunlight concentration, silver/glass mirrors are currently the only reflective material that has been proven in long-term outdoor applications [21]. Incorporation of such mirrors into viable structural elements is therefore a key to low-cost, high-performance solar concentrators.

Glass-foam core mirrors were developed by the Jet Propulsion Laboratory (JPL) in the 1970s and 1980s. With this construction, glass mirrors are mechanically deformed and bonded to a foamed glass support, which has been ground to the specified contour. The foam glass is intended to match the thermal expansion coefficient of the glass mirror [22].

Mirrors constructed of laminations of thin-glass mirrors to thick-glass supports and the use of thick-glass mirrors with inherent structural capabilities have been utilised. Examples include the ATS heliostat and the SEGS, troughs built by LUZ Corporation [23][24].

Some of most promising early efforts to develop solar mirrors were concentrated on sandwich construction. Most of this research and development on silver/glass solar mirrors was done in the late 1970s and early 1980s. In this method, membranes (such as sheet steel aluminium or plastic) are bonded to both sides of a core material. This type of construction is widely utilised in products ranging from doors and tables to aircraft and boats and is characterised by high strength-to-weight ratio. For solar applications, glass mirrors are adhesively bonded to one of the membranes. Examples of sandwich construction mirrors include the Solar One heliostat mirrors [25], the Solar Kinetics Innovative Concentrator panels [26]. the General Electric Parabolic Dish Concentrator (the PDC-l used a reflective film) [27], and the Cummins Utility-Scale dish concentrator.

Many other different technical solutions — like for instance stretched membranes — have been developed for dish concentrators [28 and 29]. However they are not easily extrapolated to linear parabolic geometry.

ENEA mirrors (Figure 6) [58] will be made of high stiffness and low weight sandwich panel materials with a thin reflecting glass surface, bonded at one side. The sandwiches are made of a central layer (core) made of aluminium honeycomb, on which two skins are bonded in order to provide adequate stiffness and shape to the whole structure. In order to limit the shear buckling, skins are made of steel, in view of its high tensile strength. The core element must have a good resistance to compression and must have good dimensional stability in time. A thin glass mirror will be lean on the skin of the honeycomb.



The shape of the sandwich itself is stable over a vast range of temperatures since the two skins have an equal temperature coefficient. Thermal expansion coefficient of the glass, are chosen to be such as to match closely the one of skins $(\sigma = (5 \div 12.5) \times 10^{-6} \ m/m^{\circ}C$, and $\sigma = 11 \times 10^{-6} \ m/m^{\circ}C$ respectively). This choice and the high elastic modulus of steel $(2 \times 10^{5} MPa)$ compared to glass $(7 \times 10^{4} MPa)$ ensure that the sandwich structure will keep its shape under ambient temperature changes.

This type of construction has the advantages of a high strength to-weight ratio, and reasonable material and manufacturing cost. The inherent stiffness of sandwich construction mirror panels also facilitates large panels. This can have cost advantages for both the amount of hardware required as well as reduced installation and alignment cost. There is little or no strain of the mirror surfaces.

A SANDIA laboratory study [30] has shown durability and lack of structural and optical degradation of $0.4 \times 0.6 \text{ m}^2$ samples of spherically curved aluminium honeycomb panels with steel skins and a reflecting glass surface. Tests ranged from exposure to elevated temperatures (> 50 °C) to thermal cycling with high humidity. Results were excellent. Slope errors were less than 0.5 mrad and spring back was minimal. Environmental testing consisted of 100 cycles between -28 °C and 66 °C with 4 hour ramps and 2 hour holds at temperature. High humidity (80%) was applied at the high temperature conditions. Minimal optical degradation resulted from these tests, which instead exclude the use of polypropylene honeycomb, of polystyrene, polyurethane, polyvinyl chloride (PVC) foams, which exhibit creep and changes in focal length if exposed to high temperature.

The considerable strength of the panels allows a reduction in the amount of structural support. The ENEA structure under consideration is indicatively constituted of individual panels of 3 x 3.5 m², made of a aluminium honeycomb core of 25 mm thickness, $\approx (0.5 \div 1)$ mm thick steel skins and a ≤ 1 mm thick silver glass panels glued on the skin.



The supporting structure (Figure 7) is made of individual modules, 12 m long, 5.76 m span. As a consequence, a set of 8(4) modules may cover a total length of about 100(50) meters. The number of modules to be clustered in a single, independent unit is of course dependent on the flatness and the geometry of the actual site.

The structure supporting the mirror surfaces (Figures 8A and 8B) is formed by hollow circular cylinder equipped with fins sustaining the reflecting surface. Such a hollow circular cylinder is a very simple and economic structure.

The centre of mass of the structure is on the rotation axis, in order to minimise the tracking power to be supplied by the motor, which has to provide the torque required to oppose friction and wind forces. Motion is transmitted by the hollow circular cylinder to the arms and the reflecting mirrors, exposed to the wind pressure.

The collector rotates around the horizontal axis, tracking the sun along its movement in the sky. A feedback tracking system, equipped with a suitable solar sensor, provides precise alignment and ensures the sun's beam radiation be focused on the linear receiver. Tracking operations are monitored by a local computer, along with the operating status, alarms, and diagnostics to be transmitted to the control room.

The structure will be designed for normal operation with typical wind speeds ranging between 40 and 60 km/h, up to a maximum of 110 km/h.



Figure 8A. Cross sectional view of the mirror assembly with the collecting tube [58].



Figure 8b. General layout of pair of modules. The central pillar holds the rotation gears, while the two auxiliary pillars provide support to the structure, which could be eventually extended by additional mirror assemblies and auxiliary pillars. Collector tubes of different modules are connected to each other by flexible joints (not shown). See Ref. [58] for more details.



Beyond such a speed limit (110 km/h), the collector must be positioned in the stowed position, forming an angle of 30 degrees with respect to the horizon.

The maximum pressure on the reflecting panel is 500 N/m² at 80 km/h wind speed, and about 1000 N/m² at 110 km/h. Early analysis shows deformations of the supporting structure smaller than 8 mm, consistent with the design value of slope changes < 1.6 mrad and stresses on the reflecting surfaces well below the glass breaking load.

Calculations were also performed for various wind directions on the whole 12 m long sustaining structure (Figure 8). The maximum deformations are << 1 cm: hence the structure is sufficiently rigid.

2.3. The Heat Collection.

The heat collection unit (Heat Tube Unit: HTU) transmits the solar heat incident on mirror's surface to the fluid which flows in it. In theory [31], for a linear parabolic geometry, the maximum ratio between the aperture and the absorbing tube diameter, the concentration factor is Γ = 214. For an aperture of 5.76 m, this concentration ratio correspond to a receiver of 2.7 cm width. Such limiting case cannot be easily realised in practice, since it has no allowance for tracking errors and for uncertainties in the shape and position of the mirrors.

Therefore, following previous SEGS's experience, the absorber tube diameter is of the order of 7 cm¹⁴ and the glass protection tube has a diameter of 11.5 cm. The glass tube is evacuated in order to ensure a good thermal insulation

¹⁴ A thinner tube, with 5 cm diameter is also under consideration.



and a long lasting reflecting deposit. The tube, made of stainless steel, has a thickness of about 3 mm, carrying a molten salt mixture (KNO₃ + NaNO₃) with a flow rate of about 6 Kg/s and at a pressure of about 5 bars. A 600 m long collector chain brings the fluid from 270 °C to about 550 °C. Its centre may be positioned at the focal line of the parabolic reflector (focal length f = 1.81 m).

Optimisation of HTU is performed in conjunction with the thermal analysis of the receiver and it depends on the optical properties of the specific coating of the heat absorbing tube. The receiver surface with ideal spectral selective properties should exhibit a step-function spectral profile: a low reflectance (high absorption) region across the solar spectrum, separated from a high reflectance (low re-emission) region at longer wavelengths. In addition it must have (1) good chemical and mechanical stability at the operating temperature, (2) long lifetime and (3) low cost and easy fabrication. High fluid temperatures (\approx 550 °C), correspond to a maximum surface temperature of 580 °C at the receiver. The optimised cut-off wavelength shifts from 2.36 mm to 1.74 mm when the receiver operating temperature increases from 400 °C to 580 °C. Commercial receivers with selective coatings optimised for an operating temperature lower than 400



°C, which is used in the conventional SEGS installations, will no longer be a good choice for higher temperatures and new coating material must be developed.

In Figure 10 we show the expected spectral performance of two typical CERMET materials under development at ENEA. It is interesting to note that one can achieve spectral behaviours of coatings with a sharp cut-off very close respect to the ideal reflectance curve.

In practice, the temperature of the tube, about 30 °C higher than the one of the fluid, grows gradually along the series connected units which constitute the heat collecting loop, from the fluid inlet (300 °C) to the collector outlet (580 °C). The performance of the ENEA type B coating is shown in Figure 11, as a function of the temperature. The possibility of dividing the collector loop in several sections with an optimised coating for each of them has been analysed and it has been discarded since it offers no appreciable improvement.

A complete analysis of the fluido-dynamical behaviour of the HTU has been performed for the tentative parameters indicated above and it is summarised in Table 2.

Solar inc. radiation, dW/dS _{neak}	900	600	300	150	015	W/m ²
Solar power for unit length	5184	3456	1728	864	0	W/m
Flow rate	6.22	4.04	1.86	0.74	0.23	kg/s
Transit time (600 m)	9.42	14.50	31.56	78.90	284.4	min
Maximum pipe temperature	564	561	558	557	289	°C
Re-emitted IR power	212	212	215	230	53	W/m
Fraction of IR re-emission	4.89	7.33	14.88	31.79		%
Pumping work	1.53	0.44	0.05	0	0	W/m
Thermal Efficiency	95	93	85	68	0	%
Total Efficiency ¹⁶	79	77	71	57	-	%
Power to fluid (after 600 m)	2473	1606	738	295	(-31.8)	kWatt

Table 2. Main parameters of HTU, integrated over the full collection length (600 m).

The main parameter is the intensity of the incoming solar radiation, which in turn determines the flow rate in the tube by the requirement that the final temperature of the fluid is 550 °C¹⁷. The IR power re-emitted by the tube depends slightly on the value of the solar incoming radiation dW/dS|_{peak}, since the longitudinal distribution of temperature depends on the flow rate. At the nominal dW/dS|_{peak}, the power loss due to radiation is a tiny 4.9 % of the solar power, but it becomes the dominant limitation for low levels of incoming solar flux. The minimum value of the solar flux for which the operation is still considered as meaningful is of the order of dW/dS|_{peak} = 150 W/m². The pumping losses are always negligibly small (~ 1 W/m !), in view of the excellent properties of the circulating liquid.

At the nominal solar flux, $dW/dS|_{peak} = 900 \text{ W/m}^2$, the solar power intercepted by the 600 m long collecting loop (50 x 12 m modules) is 3.11 MWatt.

¹⁵ This condition corresponds to night-time heat losses from the hot tube.

¹⁶ Total efficiency is based on an optical efficiency of 0.835 due to (i) a tracking error of 0.1° (0.985), (ii) the reflectance of the parabolic mirrors (0.94) (iii) the transmittance of the protecting glass (0.97) and (iv)the absorptance of ENEA B type coating.

¹⁷ We note that this is an indicative value, since the temperature may be slightly adjusted in real time during operation in order to correct the effects of lower temperatures during transient to a prescribed temperature of the hot storage.

The over-all thermal efficiency, namely the fraction of incoming solar power delivered at the end of each collecting tube is $\varepsilon_{thermal} = 79$ %. This evaluation is based on an optical efficiency of 0.835 due to (i) a tracking error of 0.1° (0.985), (ii) the reflectance of the parabolic mirrors (0.94) (iii) the transmittance of the protecting glass (0.97) and (iv) the absorptance of ENEA B type coating (0.93) and it takes into account both (v) IR-radiative losses and (vi) the (electric) power needed to run the pumps. Therefore the thermal power collected at the end of the 600 m long loop is as much as 2.457 MWatt. The fluid flow rate of a single loop is 6.22 kg/s, corresponding to 3.6 l/s. The required volume of storage is therefore about 12.9 m³ for each hour of accumulation.

For smaller values of dW/dS|_{peak} the efficiency $\varepsilon_{thermal}$ is reduced since thermal losses are about constant, reaching $\varepsilon_{thermal}$ = 56 % at the lowest, practical solar flux of dW/dS|_{peak} = 150 W/m². Therefore the value $\varepsilon_{thermal}$ = 2/3 of paragraph 1.2 is conservative.

The molten salt has a freezing point at about 240 °C and therefore the full tubing network should be kept warm during extended idling periods at about 290 °C, the temperature of the cold storage tank. A scenario in which the tubes are warm at all times is otherwise advisable, since it reduces the thermal excursion and therefore the thermal stresses of the HTU. This "idling" case, corresponding to $dW/dS|_{peak} = 0$, is illustrated in the last column of Table 2. The residual thermal (radiative) losses at 290 °C are of the order of 50 W/m, e.g. about 2 % of the nominal collected thermal power. The corresponding flow rate is very modest e.g. 0.23 kg/s and the loop may return eventually the liquid to the cold storage tank.

Depending of the duration of the idle periods, it may be advisable to introduce the "night-cap", a highly reflective screen which is located inside the vacuum tube and it is deployed during the night-time, idling period. In the retracted position (daytime) the screen covers only the unexposed angular range of the collecting tube. A night-cap of 9.25 cm diameter, with a emissivity $\varepsilon = 0.02$, thermally floating between the inner tube at 563.1 K (with ENEA type B coating) and the outer glass ($\varepsilon = 0.84$) at 300 K, will assume a temperature of 362.2 K. The corresponding heat loss will be of 5.77 W/m, about a factor 10 smaller than without the cap, bringing the level of the radiative heat leaks of the HTU to a negligible level.



At the nominal solar flux, the speed of the liquid through the pipe is 0.903 m/s, corresponding to 13.24 minutes of transit time over the 600 m long loop. The response time to variations of sunlight conditions is of such order of magnitude and it is sufficiently short. In Figure 12 we show the response to a 1 hour long irradiation step with $dW/dS|_{peak} = 900 W/m^2$, starting from an initial uniform temperature of 270 °C. The speed of the flow is matched to the solar input.

As already mentioned, we are considering the possibility of reducing the HTU collecting tube diameter from 7 to 5 cm. This will introduce a negligible loss of sunlight collection (0.98) but it would almost double ($(7/5)^2 = 1.96$) the speed of flow, thus almost halving the response time, improving the response to transients. In addition the radiated IR power, both during operation and during idling times will be reduced by a factor 5/7 = 0.714.

A method should be devised to unfreeze a tube in which the salt may accidentally become solid. The projected method is electric heating, e.g. passing some low voltage, high current through the walls of the low conductivity steel tube. Current could be supplied either directly or by induction.

The molten salt may give rise to corrosion processes, especially at high temperatures. The molten nitrate salt is made of 60% NaNO₃ and 40% KNO₃ (m.p. 220 °C) and it is operated between 290 °C and 565 °C (ΔT = 275 °C).

A 11 cm	Temperature	Corrosion rate ,	Years for
Alloy	(°C)	mm/y	1 mm loss ¹⁸
Carbon steel	460	0.120	8
2.25Cr-1Mo	460	0.101	10
	500	0.026	38
9Cr-1Mo	550	0.006	167(*)
	600	0.023	43
Aluminized Cr-Mo Steel	600	< 0.004	>250(*)
12Cr Steel	600	0.022	45
304SS	600	0.012	83
316SS	600	0.007-0.010	100 -143(*)
	630	0.106	9
800	565	0.005	200(*)
	600	0.006 - 0.01	100 -167(*)
	630	0.075	13
600	600	0.007 - 0.01	100 - 143(*)
	630	0.106	9
Nickel	565	> 0.5	< 2
Titanium	565	0.04	25
Aluminium	565	< 0.004	> 250(*)

Table 3. Corrosion speeds of metals under molten 60% NaNO3 and 40% KNO3(from Ref.[16]).

(*) corrosion rate less than 1 mm for century.

A considerable amount of information is available in published literature [32 and 33]. Corrosion and mass transfer behaviour have been investigated using a thermal convection loop to study Alloy 800, 304SS and 316SS for thousand hours. The rate of metal loss are typically $5 \div 12 \,\mu$ m/year at 600°C. The mechanism operating is mainly oxidation and in a much lesser grade a direct metal dissolution. Chemical analysis of melt demonstrated dissolution of chromium while iron and nickel were negligibly soluble. Due to the fact that the solubility of chromium, as chromate, in molten nitrate is quite large, it was

¹⁸ This figure of 1 mm maximum corrosion should allow a good estimate of the acceptable lifetime of the tube, to the extent that the initial design thickness is 3mm. In other words, we believe that the condition that less than 1 mm is corroded away is reasonable.

concluded that a passivating mechanism is in operation and it reduces kinetically the corrosion rate. No thermal-gradient mass transfer was observed. At temperature of 615 °C and 630°C, dissolution becomes linear and no limiting factors operate anymore. Corrosion rate was of 75 μ m/year for alloy 800 and 100 μ m/year for 316SS at 630°C. These temperatures are however above the operating range considered.

A specific programme was developed at SANDIA laboratory of Livermore, to test a variety of metallic and not metallic materials in the range of temperature from 300 up to 600°C [31] using crucibles for long term experiment at constant temperatures. Results are summarised in Table 3. Alloy 800- and 300- series Stainless Steel show good corrosion resistance. A typical choice for the collection tube could be for instance 316SS, which should undergo a corrosion depletion of ≈ 1 mm in over a century. Carbon steel instead is not recommended, since already at lower temperatures (460 °C) it exhibits a substantial corrosion rate.

2.4. The choice of the energy storage fluid.

In solar energy technology, several heat transfer fluids (HTF) have been utilised as carrier between the solar source and the process. With the increase of temperature over 400°C, organic fluids as mineral oil, silicone oil and organic salts can not be utilised because thermal instability of these substances. An important advantage of the molten salts is that they can be utilised both as HTF and heat storage medium, removing the need of an heat exchanger and the associated temperature losses. Among the available salts suited to the temperature range 400÷600 °C, nitrate salts present convenient thermodynamical characteristics and acceptable cost.

In early thermal solar applications (CESA 1 (Almeria-Spain) [34] and Themis (Targasonne, France) [35], the mixture of nitrite-nitrate was used only as storage medium. This ternary mixture of sodium and potassium nitrate and sodium nitrite is useful up to a maximum temperature of 450°C since corrosion problems arise above such a limit.

A binary mixture of sodium and potassium nitrates widely used in industry – stable up to a temperature of 600°C without relevant corrosion problems – was chosen for the "Solar Two" [19] power plant (Barstow, California) both as HTF and as energy storage medium. Based on this extensive experience on the binary mixture of NaNO₃ and KNO₃ a new plant ,"Solar Tres" (15 MW), is about to be realised in Cordoba (Spain) [36].

More recently, a ternary mixture of sodium, potassium and calcium nitrates have been proposed because it has a lower melting point and promises good


behaviour with respect to its decomposition and related corrosion phenomena. Moreover, it can offer improvement in a combination of characteristic such as low vapour pressure, high density, low melting temperature and low chemical reactivity at a relatively low cost. In the following, relevant aspects and physical properties of the three systems will be reported and evaluated with the aim to set the best one that matches the specifications of our plant.

The phase diagram of the system $KNO_3 - NaNO_3 - Ca(NO_3)_2$ is shown in Figure 13 [37]. The binary mixture $KNO_3 - NaNO_3$ shows an eutectic behaviour with a minimum melting point of 227 °C. Such a mixture typically 60% NaNO₃ and 40% KNO₃, though the exact proportions are not critical, has been very well studied and it has been found to be thermally stable up to about 600 °C. At these temperatures, as shown in Table 3, several types of commercial steel (f.i. 316-SS) exhibit little or no corrosion, mainly due to oxidation rather than to direct metal dissolution. If the temperature is raised further, for instance at 630 °C, some chemical decomposition causes a very quick onset of corrosive mechanisms. It is concluded that a reasonable operating range for this compound is between 290 °C and 565 °C ($\Delta T = 275$ °C).

Various mixtures are under consideration:

 i) KNO₃-NaNO₂ The mixture most frequently used is generally referred to as Heat Transfer Salt and commercially sold under a number of trade names. Its composition and melting point are respectively 53%w KNO₃ – 7%w NaNO₃ – 40%w NaNO₂ and 142 °C. It is rather stable up to 450°C; at higher temperatures a thermal decomposition of NaNO₂ is observed. When the mixture is in presence of inert gas or N₂ one observes the reaction 5 NaNO₂ \Leftrightarrow 3 NaNO₃ + N₂(g) + Na₂O. In presence of O₂ oxidation of nitrite one observes the reaction: 2 NaNO₂ + O₂(g) \Leftrightarrow 2 NaNO₃. The presence of CO₂ produces alkali carbonates which introduce minor changes in the melt. But, depending on the amount of metallic impurities present in the nitrate salts, carbonates can be formed that can precipitate in the cold part of an exchanger. In any case, the main observed variation is the progressive transformation of nitrite to nitrate that enhances the viscosity and the freezing point of the mixture, and changes the heat transfer coefficient.

ii) KNO₃-NaNO₃. The eutectic mixture is composed by 56%w KNO₃ - 44%w NaNO₃ and it melts at 227°C¹⁹. However the most frequently used composition is: 40%w KNO₃ – 60%w NaNO₃ with a freezing point of 238°C, since it is cheaper than the eutectic mixture. The melting point is sufficiently low to be conveniently used in solar plants both for cooling fluid and for storage medium.

Since molten nitrate salts may undergo a variety of reactions depending on the temperature and the composition of the cover gas, a qualification programme is necessary to ensure a long-term use. A great deal of data are published concerning the physical characteristic and thermal stability of such mixtures, so that the global picture is rather well defined [38 and 39].

The primary reaction is the decomposition of nitrate to nitrite and oxygen NO₃ (·) \Leftrightarrow NO₂ (·) + 1/2O₂(g). Its equilibrium constant and enthalpy change (23.03 Kcal/mol) were experimentally determined up to 600°C. As an example, when the mixture is exposed to air the nitrite concentration is about 3% at 565°C and about 7% at 600°C.

A variety of covering gases were analysed and air at atmospheric pressure was found the more adequate to minimise the nitrite formation. The importance of minimising nitrite arises from the fact that it decomposes producing alkali oxides whose concentration rapidly rises over a temperature of 600°C. Oxide ions are known to be very corrosive so that, a maximum working temperature must be set at 600°C.

The use of air as covering atmosphere implies that CO_2 can interact with nitrate melt to produce alkali carbonates that are highly soluble

¹⁹ The freezing and the melting points are coincident for the eutectic mixture.

but introduce minor changes in the melt. A problem can arise from the amount of metallic impurities as already discussed above for the ternary mixture nitrate/nitrite. Water can come in contact with the melt, but no hydrolysis is observed up to 600°C [40] and moreover its dissolution is completely reversible.

KNO₃-NaNO₃-Ca(NO₃)₂. The introduction of calcium nitrate in the iii) binary nitrate mixture produces a lower melting point even if enhanced cost per unit weight must be accepted. The eutectic composition and its melting point are 30% w KNO3 - 7% NaNO3 -63%w Ca(NO₃)₂ and 133°C respectively. Usually, to reduce the mixture cost, its composition is varied reducing the calcium nitrate content. As an example, at Sandia National Laboratory of Albuquerque, in the case of the "Thermocline Thermal Storage Test" [41] the selected composition was 46% w KNO₃ – 24% NaNO₃ - 30% w $Ca(NO_3)_2$. The mixture melts in the range from 140 to 160 °C when using reagent grade products and from 120 to 140 °C if commercial grade nitrates are used. Thermal stability of such mixtures promises to be quite good showing similar behaviour that is observed in the binary system up to 500°C. Above 500°C, a problem could be encountered in the ternary salt due to the low solubility of Ca(OH)2 in molten nitrate that is 1x10⁻³ molar at 300°C. Calcium oxide is produced by decomposition of calcium nitrate. Water presence, then, can form solid calcium hydroxide that, at sufficiently high concentration can precipitate causing fouling. As a consequence an enhancement of the molten freezing point can be expected. Moreover industrial producer claims the formation of crust on the vessels and piping walls above the indicated temperature.

A first estimate of perspective costs of three salts is presented in Table 4 [42].

Composition	Commercial Denomination	Cost \$/kg	ΔT °C	Cost@∆T \$/kWh
60/40, Na/K Nitrate	Solar Salt	0.49	270	4.29
7/53, Na/K Nitrate, 40 Na Nitrite	Hitec	0.93	200	10.7
42/15/43, Ca/Na/K Nitrate	Hitec XL	3.49	200	44.4
Diphenyl biphenyl oxide (min. oil)	Therminol VP-1	3.96	100	57.5

Table 4. Perspective costs of different storage media (ΔT is the temperature difference).

The final choice of the nitrate composition will be decided later on: for the moment all designs are based on the more conservative binary mixture 60% NaNO₃ and 40% KNO₃ which offers the best cost to performance ratio.

2.5. The Heat Storage Unit: functional analysis.

As already pointed out, the Heat Storage Unit (HSU) performs the important function of transforming the intrinsically variable solar energy resource into a fully "dispatchable", smooth energy source.

Discontinuities, may be roughly divided into four broad classes: (i) accidental, unpredictable, generally short term, interruptions of direct solar intensity due to clouds movements, during an otherwise productive day; (ii) the night-time idling period; (iii) bad days, due to adverse weather conditions; (iv) seasonal variations, related to the yearly cycle.

While variations of types i) and ii) may be completely smoothed out by an energy storage of a few tens of hours, type iii) may require several days of storage, depending on the location of the installation and finally type iv) are not compensated with storage. *They should be taken into account in the exploitation schedule as an inevitable characteristic of the cyclic nature of the solar power.*

In a favourable location, at a sufficiently equatorial latitude, variations of type (i), (iii) and (iv) are small and the day-night cycle (ii) dominates. Therefore we consider the effect (ii) first.

We wish a full compensation of effect (ii), namely the conversion of the natural distribution of solar power $\Phi(t) \ge 0$ into the required (uninterrupted) delivery pattern of power $\Psi(t) \ge 0$, with the help of the energy storage containing at the time *t* an energy *S*(*t*). In absence of fluctuations of type (i), (iii) and (iv), both power functions have daily periodicity and energy conservation implies $dS/dt = \Phi(t) - \Psi(t)$ which by integration gives

$$S(t_{1}) = \int_{t_{o}}^{t_{1}} [\Phi(t) - \Psi(t)] dt + S(t_{o})$$
[1]

The integral of a periodic function is also a periodic function, which ensures that also S(t) is daily periodic. Minimum $S(t_{\min}) = S_{\min}$ and maximum $S(t_{\max}) = S_{\max}$ of the function S(t) will characterise the maximum capacity of the heat storage, $Q = S_{\max} - S_{\min}$. Minimum and maximum of the function S(t) are evidently characterised by zeros of its derivative $dS/dt = \Phi(t) - \Psi(t) = 0$, namely, for both cases, $\Psi(t) = \Phi(t)$.

During the night, $\Phi(t) = 0$; $\Psi(t) > 0$ and hence and S(t) decreases until it hits the minimum S_{\min} at time t_{\min} . The point of minimum storage occurs the



moment in which the rising sun is capable of a delivery of a peak power equal to the required deliverable power. The maximum of energy storage is in turn reached when the declining solar power crosses again the condition $\Psi(t) = \Phi(t)$ (see Figure 14). Neglecting the short time differences between t_{\min}, t_{\max} and the neighbouring points at which $\Phi(t) = 0$, the maximum capacity of the heat storage

$$Q = S_{\max} - S_{\min} \approx \int_{t_{\max}}^{t_{\min} + 24h} \Psi(t) dt \text{ since } \Phi(t) = 0 \text{ for } t_{\max} < t < t_{\min} + 24h$$

This confirms the simple consideration that storage must supply the totality of energy deliverable during the period in which the Sun is absent, which is a specified fraction of the time integrated energy supplied by the Sun. In the simplified case in which the required (uninterrupted) delivery pattern power is $\Psi(t) = W_o = const$, $Q = W_o [1 - (t_{max} - t_{min})/24h] \times (24h)$.

A typical but idealised scenario is given in Figure 14, in which we show the primary solar power $\Phi(t)$ deposited on a flat, horizontal surface, the accumulated energy S(t) as a function of the time in order to ensure a constant power delivery $\Psi(t) = W_o = const$ over the 24 hour period. The specific case, given here as an example, is for the sun's maximum altitude angle of 90° i.e. at the equator (latitude = 0) on the spring equinox (declination = 0). In such an idealised case, there are no seasonal variations and the sun rises at 6:00 a.m. and it sets at 6:00 p.m. The power collected is modulated by the projection factor of the sun light with respect to the normal to the plate, $\Phi(t) = \Phi_{\max} \sin[h(t)]$ where h(t) is the altitude angle. The daily (24 h) averaged power is then $W_o = \Phi_{\max}/\pi$, where Φ_{\max} is the peak solar power delivered at noon. Smoothing of the daily variation requires therefore the accumulation of a maximum energy $Q = \Phi_{\max} \times$ [4.21 hours] which corresponds to a maximum retention time at the nominal delivered power W_o of $t_{store} = S_{\max}/W_o = 13.22$ hours.

In general, Q will depend of the actual latitude and time of the year, the geometry of the solar collection and method of solar tracking. In Table 5 we give some results for a perspective site (Gela, Sicily, 37.5° Lat. North) and one dimensional focusing. These parameters vary only relatively slowly with the latitude of the plant, since they are determined by the most favourable time of the year.

The value $Q = 11.52 W_o x$ hour, i.e. about 12 hours of storage capacity for the nominal delivery power, is an attainable value. As we shall see, it can be realised without major installations and at an acceptable cost.

Latitude	37.5°	North
Stored energy, Q	4.19	$\Phi_{\scriptscriptstyle \mathrm{max}} \mathrm{x}$ hour
Day averaged, constant power delivered ²⁰ , W_o	0.363	$\Phi_{_{ m max}}$
Retention time t_{store} at output power = W_o	11.52	h

Table 5. Main parameters of an optimal, daily HSU.

The effects due to clouds have not been included since we take the point of view that an optimal storage system — such as to ensure a smooth, uniform energy delivery around the clock — must be conservatively designed in order to preserve fully the maximum daily collected solar energy, *in absence of clouds*. The storage capacity Q should be determined by the requirement of the "best clear day" over the year. As a consequence, especially during winter, a substantial spare storage may become available, in excess of what minimally required daily, which is not entirely useless. This excess is not necessarily wasteful, since it may be used to "average" over several days and to further reduce the weather

 $^{^{20}}$ It is assumed that solar power can be stored, only whenever it is larger than 0.1 $\rm W_{0}$.



fluctuations, which are probably likely more pronounced during the off-peak times.

Additional storage capacity, beyond what required to compensate for variations of type (ii) may be useful in order to compensate the occurrence (iii) of cloudy days. As a matter of principle, the solar installation should be located in such a way as have a negligible rate of these occurrences. However, in a non-optimal location, the need may rise of compensating them to a certain extent, with a corresponding higher capacity – and therefore cost – of the HSU. It is not possible to discuss specific procedures in a general way, since they depend on the specific weather conditions and on requirements of delivery of the utility, strongly location and application dependent. We shall limit ourselves to some qualitative considerations.

In order to evaluate the effects of discontinuities on the actual deliverable power and of the corresponding requirements on storage, we make use of actual insulation of a perspective site (Gela, Sicily) where the conditions are less than optimal. On the basis of the actually observed data during 1993 [2], we can make a simulation study of how storage can smooth the power delivery over several



days, with an adequate HSU. The top graph of Figure 15 shows the actual power collected by 1 m² of parabolic trough oriented in the North-South direction. Both the incoming solar power (left scale) and the power sent to the storage (right scale), namely $\Phi(t)$, are shown.

The delivery schedule $\Psi(t)$ is defined by energy conservation, neglecting the heat losses in the HSU. In order to evaluate the "expected" delivery schedule $\Psi(t)$, we have taken a 30 days sliding integration (averaging) window (bottom graph, Figure 15) of the power sent to the HSU. The energy in the storage S(t) is then calculated with the help of Equation [1]. The storage function is bound to be $0 \le S(t) \le S_{\text{max}}$, where S_{max} is the maximum storage capacity of the HSU. For S(t) = 0, the hot storage is empty and for $S(t) = S_{\text{max}}$ the storage is full.

One can see that with a max. storage for unit collecting area $S_{\max} \approx 6.3$ kWatth/m², the failure to deliver the schedule $\Psi(t)$ is a rare phenomenon, reduced to a very modest fraction of the operating time²¹. Evidently the fraction of yearly energy missed because of insufficient storage is a function of the ultimate storage capacity (for an unbound value of S(t) obviously there is no loss).

²¹ In practice these situations of near "zero" delivery can be significantly reduced by a slight correction of the delivery schedule, as a function of the amount of energy in the storage, S(t).

The fraction of scheduled energy $\Psi(t)$ which is actually delivered is given in Figure 16 as a function of the capacity of the storage S_{max} . Values are for the modular plant described in Section 4, with a nominal electric power in the vicinity of 40 MWatt_e. The required size in meters of a cylindrical storage volume with diameter = height is also shown. One can therefore choose the capacity of the storage as a function of the allowed missed delivery fraction. We remark that the calculated t_{store} single day storage of Table 5, would require S_{max} = 1361 MWatth²². For instance, an actual 95% delivery of the 30 days averaged schedule requires an increasing the storage maximum energy to S_{max} = 2500 MWatth, about twice the minimal capacity, which is not too extravagant.

The orientation of the solar collector units is traditionally in the direction North-South. In such a case, during the solar cycle, the assembly rotates roughly by 180 degrees, going from East to West.

Another orientation is East-West, which will enhance performance during winter and which may be considered for locations with a limited transparency during winter and at latitudes relevant to Italy. In this configuration, there are two different – seasonally dependent – mirror's angular scenarios. During wintertime, sun is generally low on the horizon and mirrors point South with an optimum, E-W orientation: at dusk the mirror's elevation starts from 0° (pointing South) and it grows up to a maximum equal to the sun's maximum altitude, gently returning toward 0° at dawn. In summertime, a different daily pattern takes over provided the sun's azimuth angle²³ ϕ_s is $\phi_s < 90^\circ$ or $\phi_s > 270^\circ$ early in the morning and late at night. In these days, the mirror must be initially looking North rather than South, as intuitive. When the sun keeps rising on the horizon and turning South ($\phi_s = 90^\circ$), the mirror elevation crosses 90° (i.e. the mirror looking at the zenith) and pursues its cycle to an angular value corresponding to the maximum sun's elevation, then gently returning toward pointing North at dawn.

The performance this configurations is shown in Figure 17, which has the same general format as Figure 15. The top graph shows the actual power collected by 1 m² of parabolic trough oriented in the East-West direction during 1993 in Gela, Italy. The bottom graph shows the scheduled energy $\Psi(t)$. For comparison, we have plot also $\Psi(t)$ for the North-South orientation, taken from Figure 15. We remark that the East-West orientation offers a more uniform yearly delivery, however at expense of a reduced collection during the summer

²² This value refers to the North-South orientation. For the East-West orientation the value is 1218 Mwatth.

²³ In our convention the sun at noon has $\phi_s = 180^\circ$ and ϕ_s grows going from east to west, i.e. as time grows.



periods. The choice between the two orientations is therefore application dependent. The requirements on the storage (see central graph of Figure 17) are however practically unchanged.

2.6. The Heat Storage Unit: practical realisation.

The HSU unit must be able to retain energy for a sufficiently long period of time without significant losses, which means that it must have an excellent thermal insulation.

A number of components and experimental systems have been field tested around the world in the last 20 years, demonstrating the engineering feasibility and economic potential of the storage technology. Since the early 1980s, sun driven installations with storage with have been field tested in Russia, Italy, Spain, Japan, France, and the United States (Table 6).

The energy storage system for Solar Two, the most recent molten salt installation, consists of two storage tanks of about 900 cubic metre each (linear

dimension *L*= 10.4 m). Tanks are externally insulated. The hot and cold tanks have linings of stainless steel and carbon steel respectively. Stainless steel cantilever pumps transport salt from the hot-tank through the heat exchanger to the cold tank. Salt in the cold tank is pumped with multi-stage centrifugal pumps to the solar receiver. The molten salt, which is a mixture of 60% NaNO₃ and 40% KNO₃ with a freezing point of about 240 °C, operates normally between maximum and minimum temperatures, $T_A = 565$ °C and $T_B = 290$ °C respectively, corresponding to a temperature difference, $\Delta T = T_A - T_B = 275$ °C. The nominal thermal capacity of the system is $S_{max} = 110$ MWatth, and the maximum thermal storage capacity per unit gross volume is dS/dV = 0.453 GJ m^{-3} .

Project	Country	Output (MWe)	Heat Transfer Fluid	Storage Medium	Operation Began
Solar Two	USA	10.	Molten Nitrate	Nitrate Salt	1996
TSA	Spain	1.	Air	Ceramic	1993
SPP-5	Russia	5.	Steam	Water/Steam	1986
THEMIS	France	2.5	Hi-Tec Salt	Hi-Tec Salt	1984
MSEE/Cat B	USA	1.	Molten Nitrate	Nitrate Salt	1984
CESA-1	Spain	1.	Steam	Nitrate Salt	1983
Solar One	USA	10.	Steam	Oil/Rock	1982
EURELIOS	Italy	1.	Steam	Nitrate/Water	1981
SUNSHINE	Japan	1.	Steam Nitrate	Salt/Water	1981
SSPS	Spain	0.5	Molten Sodium	Sodium	1981

Table 6. Main solar projects with storage.

The hot tank of Solar Two has exhibited excellent heat retention. During a month-long cool down, the temperature dropped by 75°C ($\Delta T \approx 2.5$ °C/day). Total thermal losses were of the order of dS/dt = 90 kWatt, corresponding to a decay time constant²⁴ $\tau_o = 50.9$ days.

The ENEA programme foresees a series of modular installations (see Section 3), each of them with a peak solar thermal power which is more than one order of magnitude larger than Solar Two. In order to provide a storage duration comparable to the one of Solar Two (day-night averaging), the modular

²⁴ We recall that the relative energy loss after an elapsed time interval $\Delta t \ll \tau_o$ is given by $\Delta S / S_{\text{max}} \approx \Delta t / \tau_o$

plant described in section 3 – with a nominal, continuous electric power in the vicinity of 40 MWatt_e – must be capable of storing an energy $S_{max} = 1350$ MWatth vs. $S_{max} = 110$ MWatth of Solar Two. In order to overcome less favourable variability of the solar resource in the South of Italy, the stored energy should be further extended to $S_{max} = 2500 \div 6000$ MWatth, depending on the user's demands for power continuity.

An energy storage of a much larger capacity presents no major technological barrier. As already pointed out, for a given shape and linear dimension scale *L*, the useful volume and hence the maximum stored energy S_{max} grows $\propto L^3$, while the heat leak rate grows like $dS/dt \propto L^2$, for a given insulation thickness. As a result, the decay time constant τ_o – defined $dS/dt = S/\tau_o$ and characterising the spontaneous relative energy loss dS/S after the time dt – increases as $\tau_o \propto L$. Therefore the larger container, as required in our case, offers a better time constant for energy retention. For instance a 30-fold increase of S_{max} with respect to the Solar Two installation ($S_{\text{max}} = 3300$ MWatth), namely a geometrical, linear scaling up of the Solar Two tank by a factor 3.11 to a gross volume of 26260 m³, will improve the time constant to $\tau_o = 158$ days, corresponding to an extrapolated thermal loss dS/dt = 870 kWatt.

3. – Solar Hydrogen production.

3.1. Choosing the chemical process.

A large number of chemical processes have as an end product the dissociation of water molecule into hydrogen and oxygen. The process may be either (i) a purely chemical process that accomplishes the decomposition of water into H_2 and oxygen using only heat or, (ii) a hybrid thermo-chemical process using a combination of heat and electrolysis. The thermo-dynamical efficiency for such closed cycles is at best the one prescribed by the Carnot theorem and therefore they must operate between two sufficiently different temperatures. This temperature difference is directly related to the design of the heat storage unit, if, as appropriate to any chemical cycle of a reasonable complexity, a continuous operation is preferable.

Over the last 20 years, hundreds of cycles have been proposed [7], but significant R & D has been executed on only a few. Cycles with proven low cost and high efficiency have yet to be developed commercially. Therefore the final ENEA scheme for water dissociation is still subject of further investigations, to be selected from a short list (Table 7) of several processes which hold potentials for good thermo-dynamical efficiency and for an attractive cost. Table 7 contains an indicative list of as many as nine processes to which others may be eventually added. We exclude immediately Reactions (1) and (2) and (7) since they are hybrid thermo-chemical processes which require *both* heat and electricity, though they may be of interest for some more specific applications. Remaining six processes are all purely thermo-dynamical cyclic processes with at least two reactions, in which hydrogen and oxygen are separately liberated, eventually with the addition of some intermediate reaction.

For instance in the so-called General Atomic Sulphur-Iodine process [43] – (4) in the list of Table 7 – oxygen gas is liberated by thermal decomposition of sulphuric acid at high temperature (850 °C) produced by the solar energy $2H_2SO_4(gas) = 2SO_2(gas) + 2H_2O(gas) + O_2(gas)$ which is an endothermic reaction with direct production of Oxygen. Sulphur dioxide (SO₂) and additional water at relatively low temperature (100 °C) are recombined into sulphuric acid by the so-called Bunsen reaction: $xI_2 + SO_2 + 2H_2O = 2HI_x + H_2SO_4$, which is eso-thermal. Therefore heat produced by solar energy is flowing from the first reaction to the Bunsen reaction. The Bunsen reaction transforms also iodine into hydrogen iodide, which can later be extracted by distillation and decomposed catalytically in hydrogen and iodine at the intermediate temperature (≈ 350 °C), with an essentially iso-thermal reaction.

	Name		• <i>C</i>	Reaction	F
1	Westinghouse [9]	Т	850	2H2SO4(g)=2SO2(g)+2H2O(g)+O2(g)	1/2
		Е	77	SO2(g)+2H2O(a)=H2SO4(a)+H2(g)	1
2	Ispra-Mark 13 [12]	Т	850	2H2SO4(g)=2SO2(g)+2H2O(g)+O2(g)	1/2
		Е	77	2HBr(a)=Br2(a)+H2(g)	1
		Т	77	Br2(l)+SO2(g)+2H2O(l)=2HBr(g)+H2SO4(a)	1
3	UT-3 Univ. of Tokyo [13]	Т	600	2Br2(g)+2CaO=2CaBr2+O2(g)	1/2
		Т	600	3FeBr2+4H2O=Fe3O4+6HBr+H2(g)	1
		Т	750	CaBr2+H2O=CaO+2HBr	1
		Т	300	Fe3O4+8HBr=Br2+3FeBr2+4H2O	1
4	GA Sulphur-Iodine [43]	Т	850	2H2SO4(g)=2SO2(g)+2H2O(g)+O2(g)	1/2
		Т	300	2HI=I2(g)+H2(g)	1
		Т	100	I2+SO2(a)+2H2O=2HI(a)+H2SO4(a)	1
5	Julich Center EOS [44]	Т	800	2Fe3O4+6FeSO4=6Fe2O3+6SO2+O2(g)	1/2
		Т	700	3FeO+H2O=Fe3O4+H2(g)	1
		Т	200	Fe2O3+SO2=FeO+FeSO4	6
6	Tokyo Inst.Tech.Ferrite [45]	Т	1000	2MnFe2O4+3Na2CO3+H2O=2Na3MnFe2O6+3	1
				CO2(g)+H2(g)	
		Т	600	4Na3MnFe2O6+6CO2(g)=4MnFe2O4+6Na2CO	1/2
				3+O2(g)	
7	Hallett Air Products 1965 [44]	Т	800	2Cl2(g)+2H2O(g)=4HCl(g)+O2(g)	1/2
		Е	25	2HCl=Cl2(g)+H2(g)	1
8	Gaz de France [44]	Т	725	2K+2KOH=2K2O+H2(g)	1
		Т	825	2K2O=2K+K2O2	1
		Т	1252	K2O2+2H2O=4KOH+O2(g)	1/2
9	Nickel-Ferrite [46]	Т	800	NiMnFe4O6+2H2O=NiMnFe4O8+2H2(g)	1
		Т	800	NiMnFe4O8=NiMnFe4O6+O2(g)	1/2

 Table 7. List of perspective water dissociation processes[8].

The net result of these three reactions is that water is decomposed into hydrogen and oxygen with a number of chemicals (H_2SO_4 , SO_2 , I_2 and HI_x) as circulating materials in the process.

The process has been tried so far in a small scale laboratory arrangement, though a 1 MWatt test plant has been planned in Japan. A study has been published on the possible design of a thermal plant of a pre-industrial scale for a nominal H₂ power of 225 MWatt. The numerically estimated efficiency of the process is well above 50%. This study evidences as well the primary inconveniences of this method, namely (1) the highly corrosive nature of the H₂SO₄ ÷ SO₂ gaseous mixture which requires an heat-exchanger with the solar energy supply operating at 850 °C ,(2) the high cost of the iodine to be used internally in the cycle and (3) the complex separation of chemicals by fractional distillation.

A substantial improvement is offered by process (3) of Table 7, namely the so-called UT-3, University of Tokyo process [13]. The process is based on four reaction processes [R1] through [R4], occurring simultaneously in four separate reactor chambers, which we examine in more detail.

In a pair of reactor volumes, the first two [R1] and [R2] ensure the cyclic transformation between solid calcium bromide and calcium oxide $[CaBr_2] \leftrightarrow [CaO]$ induced by gaseous reactants.

(1033 K)
$$H_2O(g) + [CaBr_2] \rightarrow [CaO] + 2HBr(g)$$
 [R1]

(845 K)
$$\operatorname{Br}_2(g) + [\operatorname{CaO}] \rightarrow [\operatorname{CaBr}_2] + (1/2)O_2(g)$$
 [R2]

In the reaction [R1] water vapour is transformed into gaseous bromidic acid, while in reaction [R2] gaseous bromine gas is transformed into oxygen. In another pair of reactor volumes, a second pair of reactions [R3] and [R4] ensure the cyclic transformation between solid iron oxide and iron bromide $[FeBr_2] \leftrightarrow [Fe_3O_4]$ induced by gaseous reactants.

(495 K)
$$8HBr(g) + [Fe_{3}O_{4}] = 3[FeBr_{2}] + Br_{2}(g) + 4H_{2}O(g)$$
 [R3]

(833 K)
$$4H_2O(g) + 3[FeBr_2] = [Fe_3O_4] + 6HBr(g) + H_2(g)$$
 [R4]

In the reaction [R3] bromidic acid is transformed into gaseous bromine gas and water vapour while in reaction [R4] water vapour is transformed into hydrogen and gaseous bromidic acid.

The four separate reactor chambers R1-R4 exchange gaseous products with the help of a common gas stream crossing in succession the four chambers, as shown in Figure 18. Temperatures are adjusted by the heat exchangers HX1, HX2, and HX3. The heat exchanger HX4 heats up the water inlet into vapour.



The whole process is driven by the solar heat which is brought in by the heat exchanger HX01, operating between the temperature of reactor R1 (1033 K) and the one of reactor R2 (845 K). Two membrane filters S1 and S2 are used to extract hydrogen and oxygen gases from the cycle. An adequate compressor C2 ensures appropriate circulation of gases in the loop. When the chemical transformations of the solid reactants have been completed, the reactors R1/R2 and R3/R4 are exchanged in order to ensure continuity of the operation which is cyclically repeated.

Kinetic studies have shown that 100% conversion of reaction [R1] requires about one hour. The other reactions have shorter times: [R2], about 10 minutes, [R3] and[R4], less than one hour. Excess steam (100 H_2O/H_2) or steam + N_2 is circulated clockwise in Figure 18, which allows each reaction to proceed without any external heat supply, supplying reaction energies by direct contact with the solid reactants.

A specific model for a capacity of 25 mol H_2/s has been reported[47]. This size is somewhat arbitrary and the size of the plant can be easily tailored to the specific application. Design parameters are shown in Table 8, taken from Ref. [13].

The process evaluation shows that the pumping power required for compressor C2, which activates the main flow through the reactors and the pumping power for the H2 and O2 extraction after the membranes requires a mechanical power of the order of 1.3 MWatt. This power can be generated with the help of a Rankine cycle from the excess thermal energy from the cycle which amounts to about 7.5 MWatt at 590/493 K.

Item	Value	Unit				
Solar parameters						
Solar field nominal peak power	45.6	MWatt				
Max receiver temperature	840 (1113)	°C (K)				
Direct solar energy	6.4	H/day				
Storage operation	12.8	H/day				
Average daily operation	19.2	H/day				
Lower storage temperature	569 (842)	°C (K)				
Thermal storage capacity	702.1	GJ				
Hydrogen Converter						
Thermal power to process	15.2	MWatt				
Thermal energy required	1053.2	GJ/day				
Hydrogen stored energy	490	GJ/day				
Hydrogen production rate	2000	Nm ³ /h				
Process system pressure	2.0	Mpa				
Hydrogen line pressure	2.5	Mpa				
Oxygen line pressure	1.8	Mpa				
Mechanical pumping work	1.347	MWatt				
Temperature excess heat	317 (590)	°C(K)				
Excess heat production	7.536	MWatt				
Over-all efficiency (Sun \rightarrow H ₂)	46.52	%				

 Table 8. Design characteristics of solar UT-3 process.
 [13]

Other, much simpler processes are under consideration, but they are so far at a more rudimentary stage. We refer for instance to processes (6) and (9) of Table 7. More generally the processes consist in a simple Redox operation in which oxygen is emitted at higher temperature inside a solar furnace, followed by a subsequent oxidation process which is performed at lower temperature with the help of water vapour, in which water is decomposed and hydrogen is liberated. In this way, the cycle is closed. In addition we may consider [48] the following chemical transformations



 $Fe_3O_4(liquid) \rightarrow 3FeO(liquid) + \frac{1}{2}O_2(gas), T > 1875 K$

The FeO is then reacting exo-thermally at lower temperature with water, to produce H_2 (Figure 19):

$$3FeO + H_2O \rightarrow Fe_3O_4 + H_2$$

The Fe_3O_4 is recycled to the solar furnace, where FeO is reproduced.

Similar processes are possible with other materials like for instance (Figure 20) the Zinc related mechanism [49]:

$$ZnO(solid) \rightarrow Zn(gas) + 1/2 O_2 \quad [2300 \text{ K}]$$
$$Zn + H_2O \rightarrow ZnO + H_2 \qquad [700 \text{ K}]$$

The decomposition of zinc oxide to zinc is an attractive process, since both products are evolved from the surface of a shrinking ZnO particle into the gaseous state. Thus in contrast with other metal oxides reduction processes, the kinetics are not limited by diffusion of ions through a condensed phase.

Both processes require a solar furnace in the vicinity of 2000 °C, for which in particular the re-radiation losses become relevant and may reduce the over-all efficiency. At much lower temperatures, one has considered the ferrite cycle [46]:



$$Ni_{0.5}Mn_{0.5}Fe_{2}O_{4} \rightarrow Ni_{0.5}Mn_{0.5}Fe_{2}O_{4-\delta} + \delta/2 O_{2} \qquad [1300 \text{ K}]$$
$$Ni_{0.5}Mn_{0.5}Fe_{2}O_{4-\delta} + \delta/2 H_{2}O \rightarrow Ni_{0.5}Mn_{0.5}Fe_{2}O_{4} + \delta H_{2} \qquad [970 \text{ K}]$$

which however has a very small value $\delta = 0.053 \pm 0.005$, namely a very small gas yield.

These processes, though much simpler than the ones described above, are at the present stage almost unexplored. In particular a number of problems need to be elucidated. In the case of the Fe₃O₄-FeO Redox process, both oxides are in the liquid form. At present it is not known if the two liquids are separate or separable or if they remain mixed. The furnace cannot have a window and therefore the reactants are most likely in the continuous presence of air, which implies the formation of NO²⁵. In the case of the ZnO-Zn Redox process, Zn (boiling point 907 °C) and oxygen are both in the gaseous form in the reactor. Recombination may occur during the extraction process, with the build-up of an additional ZnO contamination. The yield of zinc from the thermal decomposition of ZnO strongly depends on the ability to prevent re-oxidation with a fast quenching of the gaseous products.

The main virtue of these advanced methods is simplicity: in particular hydrogen and oxygen are produced in different steps, eliminating the need for gas separation.

 $^{^{25}}$ After leaving the reactor, the products may be cooled rapidly with the reformation of O_2 and N_2 from O and NO. However such a quenching process is an irreversible process causing a drop in the efficiency of the system.

All these alternatives will be the subject of a systematic R & D programme, since development of solar hydrogen production has necessarily a much longer time scale. Laboratory tests of several chemical processes must be performed before launching a solar driven prototype of several MWatt, to be constructed probably at the ENEA-Advanced Solar Laboratory LASA, presumably near Latina. In the following we shall take provisionally the UT-3 University of Tokyo as the reference process.

3.2. Solar collectors for higher temperatures.

Solar collection with parabolic concentrators (concentration factors Γ in excess to 1000 fold) can achieve substantial temperatures which are of considerable interest, since they permit both the production of hydrogen from the dissociation of water production and other applications, like for instance electricity production with a higher thermo-dynamical efficiency. Therefore the development of an adequate high temperature parabolic solar collector is amongst the long range goals of the ENEA programme in the field of thermal solar energy.

A determinant parameter in the definition of the thermal collectors is the operating temperature. Two target temperatures emerge from the previous considerations: (i) 850 °C with thermal storage for the UT-3 University of Tokyo process, which can be easily extrapolated from existing installations and (ii) a much more speculative approach of much higher temperatures in the order of $1800 \div 2000$ °C for the simpler, but more advanced Redox processes.

The present generation of solar air receiver (PHOEBUS [14]) have operated up to 700 °C with solar power densities of the order of 300 suns (1 sun = 1 kWatt/m²) average and 800 suns peak. Hydrogen production with the UT-3 process on the other hand requires substantially higher temperatures, of the order of 850 °C. This can be easily accomplished increasing the concentration significantly. But substantial limitations of different nature may arise at higher temperatures, which require additional R & D:

- The mechanical stability of the structural materials in the various elements, collector, heat pipes, storage, heat exchangers and so on. For instance the use of stainless steels limits the practical temperature to about 850 °C which is adequate for the UT-3 process, but not for the simple Redox schemes Fe₃O₄-FeO or ZnO-Zn. Higher temperatures are of course possible, but only with very special materials of higher cost.
- The re-irradiated power from the hot elements, and in particular of the collector, which is quickly rising according to the Stefan law. Parabolic

troughs described in section 2 make use of a special coating which is strongly absorbing for the solar spectrum and highly reflecting for the re-emitted infra-red radiation. At higher temperatures, the spectral difference becomes smaller and the two spectra begin to overlap. Therefore at much higher temperatures little or no advantage is gained from a modulated reflectivity.

The solar collector structure of the PHOEBUS installation, with a nominal power of 3.0 MWatt is an open geometry with a air cooled collector of significant size (7.0 m²) and a modest peak concentration of 800 suns. Calculated thermal losses[14] at nominal conditions (700 °C, $T_{abs}^{\kappa} = 970$ K) amount to 10.4 % radiation losses $\propto (T_{abs}^{\kappa})^4$, 6.3 % incomplete solar light absorption losses and 5.6 % of hot air conduction losses $\propto (T_{abs}^{\kappa})$. The over-all, *measured* efficiency is 68.2 %. Increasing the solar concentration and therefore the input power per unit size, the temperature could be increased to 850 °C with an acceptable over all efficiency, as required for instance for the UT-3 process, still retaining the basic design parameters.

The PHOEBUS installation has also a thermo-cline pebble bed heat storage of $M_{storage} = 18$ ton (8.3 m³) of ceramic pellets with a capacity Q = 1 MWatth, for a maximum temperature drop of the outlet temperature of 30 °C. It operates with a $\Delta T = (700 - 200) \ ^{\circ}C = 500 \ ^{\circ}C$. In the case of parameters suitable for UT-3 (Table 8), namely $\Delta T = 271 \ ^{\circ}C$ and a storage capacity $Q = 702.1 \ \text{GJ} = 195 \ \text{MWatth}$, the extrapolated mass is $M_{storage} \approx 18 \times 195 \times (500/271) = 6476 \ \text{ton} (2986 \ \text{m}^3)^{26}$.

Much more speculative is the possibility of reaching temperatures of the order of 2000 °C, as required by the Redox processes. However for completeness we briefly mention the main points.

In order to reach such a temperatures, the mean flux concentration must be of the order of 5000 suns. A concentration factor $\Gamma \approx 5000 \div 6000$ is within reach of large-scale solar collection facilities. The basic reactor concepts feature the following characteristics: (i) a cavity receiver configuration (Figure 20), namely insulated enclosure designed to effectively capture incident solar radiation entering through a small aperture. Because of multiple internal reflections, the cavity receiver approaches a black body absorber. Such cavity receiver configuration may reduce the re-irradiation losses to an acceptable 15 ÷ 30 % at 2000 °C. (ii) They may use the reactants for lining the reactor inner walls, in order to reduce the use of expensive and difficult to fabricate ceramic insulating materials for high temperatures. The reactor must withstand thermal shocks, since no storage is possible and a short start-up is required. (iii) the reactants

²⁶ Eventually materials cheaper than the ceramic pebbles could be used.



offer direct absorption of the concentrated solar energy, which is irradiating directly the reactants, bypassing the via heat exchangers.

Such a high concentration factors obviously require a very advanced solar concentrator in two dimensions, namely a circular revolution parabola. Two arrangements are therefore possible, either a Solar tower or an assembly of independent parabolic concentrators. As already pointed out in section 1.4, ENEA approach is concentrating on the latter choice, taking also into account the possibility of sites for which the general geometry of a high solar tower illuminated by a large number of eliostats may not be easily applicable.

А number of different realisation technologies for parabolic concentratorshave been reported, which are briefly reviewed. Steel-substrate supports with glass mirrors bonded to a steel sheet, which in turn are supported by a stretch-formed or stamped steel backup structure (like a car hood) were used in the McDonnell Douglas dish concentrator [25]. Similar approaches, but with rib supports stretch-formed or stamped to the desired curvature, were used by Acurex in their Innovative Concentrator design and by Solar Kinetics, Inc. (SKI) on the Shenandoah dishes. Both of these concentrators used reflective film [50 and 51]. Fibre-glass supports formed over a mandrel have been investigated recently by Kansas Structural [52] and McDonnell Douglas [53].

Stretched-membrane designs incorporating membranes of plastic or steel stretched over both sides of a ring have received a lot of attention. In the stretched membrane design, vacuum in the plenum between the membranes is drawn to create curvature. Examples include LaJet/Cummins facets, the SAIC USJVP dish and several heliostat designs. [28 and 29]. Stretched-membrane concentrators with plastically deformed metal membranes, for short focal length to diameter ratios, have been developed by Solar Kinetics, Inc. [26] and Schlaich, Bergermann, und Partner [54].

Two main concepts have been retained for further consideration by ENEA, namely (i) the stretched-membrane concentrators and (ii) the honeycomb support to a thin glass mirror surface, in analogy to the technology under consideration in section 2 for the parabolic troughs.

In analogy with a design by Schlaich, Bergermann, und Partner (Figure 21) we have chosen a dish diameter of 17 m, corresponding to a collection surface of 227 m². At the nominal peak solar flux of 900 Watt/m², the solar incoming power is 200 kWatt.

In order to fulfil the requirements of Table 8, namely a 45.6 MWatt peak solar power, an assembly of \approx 230 of such mirrors is required. The heat storage may be either centralised or alternatively a storage unit of the size designed for PHOEBUS [14] may be used for each separate dish.

3.3. Conclusions

Hydrogen production with thermal solar technology is a vast and innovative programme which requires a considerable amount of R & D. There is no doubt that new solar collectors with high temperatures are necessary, which excludes the use of parabolic trough and requires the development of parabolic dishes with a very high flux concentration.

Although many reactions have the potentials for an economically attractive solution, no single alternative can today be considered as capable of an industrial development phase.

A few cycles, like for instance the Sulphur-Iodine and UT3-Tokyo University hold potentials for an operating temperature of about 850 °C, but are still relatively complex and require continuous operation after a heat storage. Much simples cycles, like the several Redox cycles, are much simpler, but they require very high temperatures of the order of 2000 °C.

In view of the strategic importance of solar driven hydrogen production, ENEA is poised to an aggressive R & D programme, in order to make the basic choices, precursory to industrialising a chosen process.

4.— The demonstration facility for grid electricity production.

4.1. General parameters.

A full scale power plant demonstration facility of adequate power is one of the main milestones of the ENEA strategic plan. Such a plant is intended to be the prototype for a more general deployment of commercially viable facilities in the south of Italy and elsewhere.

The plant can be functionally divided in two thermal loops (Figure 22): (i) the first, primary loop, which includes solar parabolic collectors, piping, two thermal energy accumulators and one heat exchanger; (ii) the secondary loop which carries steam at 100 bar pressure and 525°C temperature to the dedicated application, which has been exemplified with electricity production.

The plant, described in more detail in Ref. [58], is made of one or more identical modular units, each one designed for a nominal peak thermal peak solar power²⁷ of 321 MWatt, a daily averaged power after storage²⁸ of 94 MWatt_t and a nominal, time averaged, gross electric power of 40 Mwatt_e, assuming a thermal cycle efficiency of 0.42.



Figure 22. Schematic of the Primary and Secondary Loops, which store and transform thermal solar heat into a continuous supply of electricity, by means of high temperature (525 °C) steam.

 $^{\rm 27}$ Such a value corresponds to the nominal, maximum direct solar irradiation of a clear day of 0.9 kWatt/m^2

²⁸ This relates to the typical conditions of south Italy, with an equivalent insolation duration at nominal irradiation of 7.1 hours, in order to take into account for the non optimal location.



The solar field is organised into three sections, made of 33, 33 and 70 loops respectively. Each loop is composed by 6 collectors, having a gross length of 600 m, with the general characteristics described in Table 2. The total active collecting mirror length is 78.3 km, corresponding to a useful collecting area of 0.451 km².

A possible general layout of the solar installation is shown in Figure 23. The total land surface dedicated to the mirror fields, with collecting units spaced about two mirror's width, is about 0.9 km^2 . Including all other installations and auxiliary buildings, the projected over-all site dimensions are $0.72 \times 1.68 = 1.210 \text{ km}^2$. The energy collected from the solar field is used in a Rankine steam turbine/generator cycle. A heat exchanger generates high pressure and temperature steam. The exhausted steam is condensed, preheated and returned, through a condenser to the heat exchanger. An auxiliary boiler may eventually provide a backup fossil-fired capability, whenever required.

4.2. Solar field layout.

Existing solar power plants are generally located in desert areas where land cost and availability do not present serious problems. In such regions, the solar



collecting strings are normally aligned along the North-South direction and spacing between adjacent rows can be made large enough in order to minimise projected shadows. It may be difficult, in the perspective sites of the ENEA programmes, to find an adequate extension of such a flat land and at a negligible cost.

The effects due to the shadows cast by mirrors have been evaluated for a Sicilian locality at 37° North latitude (Figure 24). The optimal, compacted configuration is oriented in the N-S direction and with a spacing equals to twice the aperture of the solar collecting mirrors, although the E-W configuration, though not optimal, may also be retained, would it be required by the specific land configuration.

In order to evaluate the actual performance of the plant, a full yearly simulation of the receiver operation has been carried out for the chosen location. Receiver and salt temperatures have been calculated and they are shown in Figure 25. A simple control algorithm has been used in order to adjust the salt mass flow consistently with the objective of maintaining the output temperature of the fluid at 550 °C. We remark that the residual time dependence will be completely smoothed out by an adequate thermal storage unit.

4.3. Over-all efficiency considerations.

The global efficiency η_{global} of the full transformation of solar energy into electricity is a parameter of primary importance²⁹. For an ideal, maximum solar

²⁹ η_{global} is referred to the solar energy incident into the collectors plane. Alternatively, it is possible to calculate the global efficiency using the direct normal irradiation as reference value, in



Figure 25. Actual solar irradiation and hot salt temperature at the exit of the solar string before entering the thermal storage unit, as a function of time for the month of June and a Sicilian locality at 37° North latitude.

yield of $dW/dS|_{peak} = 900 \text{ W/m}^2$, according to Table 2, the over-all (theoretical) efficiency of heat transfer, namely the fraction of incoming solar power delivered at the end of each collecting tube is $\varepsilon_{thermal} = 79$ %. However in order to take into account of other losses due to storage, night time cooling, transients and so on, the more conservative value of $\varepsilon_{thermal} = 2/3$ has been used. Therefore $\eta_{global} = 0.666 \times 0.41 = 0.27$, which is a remarkably high value.

A more detailed analysis [55 and 56], related to the actual insolation of a perspective site (Gela, Sicily) where the conditions are less than optimal, is given in Figure 26. In these calculations one has taken into account the realistic solar yeld for the indicated location. We remark the contribution of the newly developed coating for a higher operating temperature, which permits a higher $\eta_{global} = 0.235$ value, slightly lower than the optimal conditions which give $\eta_{global} = 0.27$.

It is worth comparing this performance with the alternative of a PV array, followed by electricity storage in batteries or otherwise as discussed in paragraph 1.6, with an estimated efficiency of 0.5. The efficiency of the PV panel conversion in electricity may be estimated to be 0.12^{30} . Therefore $\eta_{global} = 0.12 \times 0.5 = 0.06$, which is a factor 4 lower than the one of thermal solar. This PV installation will

this case the η_{global} here presented is to be multiplied by the ε_{angle} introduced in section 1.2. For the perspective site under consideration $\varepsilon_{angle} = 0.82$.

³⁰ It should be recognized that PV is equally sensitive to diffused light and therefore applicable to a wider range of locations.



also have a much larger cost, both for the solar collectors and for the electric storage.

4.4. Solar Field collecting network.

A rather extensive network is necessary in order to transfer the fluid from/to the solar units. Pumps are symmetrically located in the middle of the four sections of the solar field. The main piping has an average diameter of 200 mm, while the secondary piping has an external diameter of 70 mm.

All piping system is covered with insulation coating (thermal conductivity $0.06 \text{ W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$) having a depth of 150 mm.

The total length of the network piping is 6744 m, of which 3264 m are secondary piping. Such a configuration has the advantage of making the management of the solar field more adjustable during operation, facilitates installation and controllability and making smaller the diameter of the main piping, so reducing the pressure.

Average linear thermal losses are 112 Watt/m, while the global loss of heat results of about 752 kWatt_t that is the 0.23 % of the peak thermal power. In the night-time the fluid circulation kept in operation in order to avoid the



solidification salt and to maintenance the average temperature about at 280 °C. In these conditions the linear heat losses are 72 Watt/m (0.22 %).

4.5. Thermal storage.

Thermal storage (HSU) has been extensively discussed in paragraph 2.5. The storage tanks must store a large volume of hot fluid in safe conditions with low heat losses. A modular storage capacity of 3000 MWatth has been assumed. Such a tank would contain 14770 m³ of liquid and have a thermal storage capacity of 10800 GJoule, e.g. the equivalent of 342 m³ of fuel-oil. *With a typical conversion efficiency into electricity of 0.41, such a storage could maintain alone a continuous electricity production of 40 MWatt_e during 3000 x 0.41/40 = 30.7 hour³¹s. We recall that in order to correct for the standard day-night cycle, according to Table 5 one needs a retention time t_{store} =13.22 hours. One single modular HSU can smooth out realistically all major fluctuations ensuring 95 % scheduled delivery in a less than optimal location as it is the case for Gela, Italy, as shown in*

³¹ The same volume of 14770 m³ of fuel oil will operate the plant for 55 days. It is unrealistic to assume that oil refueling in a standard power plant could occur with a shorter frequency. Hence the HSU and a perspective oil tank for a plant of this power are quite comparable !



Figure 16. Eventually a second modular unit could be installed, would more stringent requirements of delivery arise.

A straightforward extrapolation from the HSU of Solar Two [19] would give a daily temperature loss of the full storage, i.e. the natural decay, as small as $dT \approx 1 \text{ }^{\circ}C/day$ with the energy loss time constant τ_a approaching one year.

A typical realisation scheme for the hot storage tank is shown in Figure 27 [35]. The tank is insulated with a corrugated liner, an inside refractory brick and an outer fibre insulation. The concrete foundation is cooled by a water circuit.

The main design parameters have been based on the mixture 60% NaNO₃-40% KNO₃ at 550 °C with a specific heat capacity $c_p = 1529$ J/kg K and a density d = 1739 Kg/m³. For $\Delta T = 275$ °C the storage capacity per unit volume is dE/dV = 0.731 GJ m^{-3} . The active liquid volume is therefore 14770 m³, corresponding to D = 30 m and H = 21 m (Figure 27).

The thickness of the insulation determines the thermal heat losses. In order to determine the order of magnitude of the thickness of insulation, we assume the heat conductivity of ceramic fibre at a mean temperature of 400 °C, $\lambda = 0.095$ W/m K (for bricks $\lambda = 0.112$ W/m K). An energy decay constant $\tau_c = 1$ year is attained with an average insulation thickness of $s_1 + s_2 \approx 50$ cm. Of course the actual design will have to take into account all the details of construction and of a cost optimisation. However it is clear already at this stage that an appropriate HSU can be realised with simple, conventional technologies [57].



4.6. Thermoelectric conversion

The behaviour of the thermal cycle depends on several parameters. Some considerations are reported below about a few of these parameters, in order to select the best values to be used in the thermal cycle analyses. All the analyses have been performed by the GATECYCLE computer code.

The efficiency of thermal cycle strongly depends on steam conditions and grows when both pressure and temperature increase. The steam temperature is affected by the temperature conditions in the hot storage tank and the characteristics of the steam generators (terminal temperature difference, TTD). Assuming a maximum fluid temperature of 550 °C and a TTD in the steam generator of 25 °C, the resulting steam temperature is 525 °C.

We display in Figure 28 the thermal efficiency and the steam quality, as function of the pressure (one steam superheating). The steam may cause erosion phenomena on the turbine blades, if the quality drops below a value of about 0.86. Pressure values up to 100 bar are acceptable. A second steam super-heater, after expansion in the high pressure turbine, may be a solution to the erosion problems, since in this case the steam quality remains above 0.95.

As the result of an extensive optimisation procedure, both for single and double steam superheating we find an optimum thermal cycle efficiency of 0.423 at 120 bar and 525°C, for a steam mass flow-rate of 33.1 kg/s. After expansion in the high pressure turbine (up to 24 bar), about 89% of the steam flow-rate (29.5 kg/s) is re-circulated to the steam generator, where the initial temperature conditions are restored. The thermal power supplied to the steam generator is 94.5 MWatt, 85% of which is needed for steam generation and superheating and 15% for the further steam superheating.

The total steam flow-rate extracted from the turbine (5 feed-water heaters and 1 de-aerator) is 9.7 kg/s – about 29% of the total mass flow-rate – required to heat the feed-water to 231°C. A steam mass flow-rate of 23.4 kg/s is sent to the condenser, with a quality of 0.95. The thermal power needed for steam condensation is 54.2 MWt. The related cooling flow-rate is about 5,800 m³/h, assuming an increase of water temperature equal to 8 °C.

The power needed for the three circulation pumps is 906 kW. In Figure 29 the thermal cycle on the Temperature-Entropy diagram is shown.

4.7. Conclusions.

A generic power plant has been conceived as made of a number of modular units. The main parameters of each module are summarised in Table 9 for the location in Gela, Italy. Performance for both North-South (N-S) and East-West (E-W) mirror orientations are listed, for a given peak electric power delivery. Since the maximum occurs during the summer, and the solar collection efficiency during this period is higher for the N-S orientation, the surface of collectors is slightly larger for the E-W orientation.

Since the power delivery for the E-W orientation is flatter over the year, the yearly delivered electric energy is 198 $\text{GWatth}_{e}/\text{y}$ and 168 $\text{GWatth}_{e}/\text{y}$ respectively for the E-W and N-S orientations. In Figure 30 we show the 30 days averaged power for m² of parabolic trough in both orientations for Gela, Italy and a more favourable location (Albuquerque, US). The yearly averaged power is for the Italian site is only about 63 % of an optimal location. This has evidently some repercussion on the cost of electricity.

A modular storage (HSU) of 3000 $Mwatth_t$ (14770 m³) has been assumed. Such a storage could maintain alone a continuous electricity peak production during t_{store} = 30.7 hours. We recall that in order to correct only for the standard day-night cycle, a retention time t_{store} =13.22 hours is required. The large HSU capacity should ensure that the unscheduled power delivery due to bad sun's conditions is less than 5% (see Table 9). Adding another 5% unscheduled delivery due to failures of the rest of the system, we expect an actual yearly electric energy production of 183 GWatth_e/y and 157 GWatth_e/y respectively for the E-W and N-S orientations, corresponding to an average capacity factor³² of 52%.

	EW	NS	
Number of collectors	1008	816	
Total collectors area	5.57	4.51	$x10^{5} m^{2}$
Collectors spacing	11.52	11.52	m
Solar field area	11.1	9.4	$x10^{5} m^{2}$
Solar field peak power ³³	396	321	MWatt
Salt flow rate at peak power	997	807	Kg/s
Distribution network length	6.6	6.6	km
Solar energy on the collector plane	737	639	GWatth/y
Solar energy transferred to molten salt ³⁴	492	427	GWatth/y
Maximum deliverable power (30 d average)	93	94	MWatt
Storage capacity	3000	3000	MWatth
Delivered thermal energy fraction	95.5	96.7	%
Delivered thermal energy	470	413	GWatth/y
Electric nominal power	40		MWatt
hermoelectric efficiency at nominal power 42.3		%	
Thermoelectric efficiency at 0.7 nominal power	41.6		%
Thermoelectric efficiency at 0.3 nominal power,	38.3 %		%
Condenser cooling flow rate	5808 m ³ /1		m ³ /h
Delivered electric energy	193	168	GWatth/y

Table 9. Main parameter for modular power plant operating in Gela, Italy.

 $^{^{32}}$ Continuous, idealised electricity delivery the peak power is 40 MWatt x 24 hrs x 365 days = 350 GWatth.

³³ At 900 W/m² and an heat collection efficiency of 79%(Table 2)

³⁴ With an yearly average efficiency of 66.7%, conservatively lower than the figure of Table 2.



It is worth comparing this performance with a natural gas combined cycle (NGCC) conventional plant and state of the art gas turbine. We assume an average capacity factor of 80%, a 10% discount rate, a 25 years plant life, an annual insurance rate of 0.5 %, neglecting taxes, so that the annual capital charge is 0.1152. The efficiency of such a conventional plant is 50%. The incidence of a 5.5 \$/GJ cost of fuel (natural gas)³⁵ to the electric generation cost is then 3.94 US¢/kWatth³⁶.

As already pointed out (see Figure 5) the solar plant is a substitute for the high temperature heat of a fossil-fired plant. In order to ensure that the solar plant may produce electricity at competitive prices, the service to the capital investment of the (i) solar field, (ii) heat collection and (iii) heat storage must match the cost of fuel for the NGCC plant – the cost for subsequent electricity production and O&M being roughly the same for the two schemes under comparison. Converted into effective capital servicing, the figure of 3.94 ¢US/kWatth corresponds to a capital cost of 2395 \$US/kWatt, which must not be exceeded by the above items in order to produce electricity with the solar field in

³⁵ Natural gas prices hit 10.00 US\$/GJ in January, after averaging about \$2.50 US\$/GJ for most of 1998–99. Although natural gas prices have declined, they remain much higher than earlier levels.

³⁶ The resulting electricity generation cost is composed of: capital, 0.77 ¢US/kWatth, Fixed O & M,0.23 ¢US/kWatth, Variable O & M, 0.15 ¢US/kWatth, for a total cost of 5.09 ¢US/kWatth.
a way competitive to natural gas. Correcting for different capacity factors, for the modular plant of Table 9 we find $0.52/0.80 \times [2395 \text{SUS/kWatt}] \times 40'000 \text{ kWatt} = 62.3 \text{ Million $US}.$

According to Table 4, the cost of the storage fluid alone (binary mixture 60% NaNO₃ and 40% KNO₃) is 0.49 US/kg or 8300 US/m^3 , corresponding to 12.4 Million US^{37} for the required volume of 14770 m³. Adding some 7.6 Million US for the storage tanks and associated equipment, we find an indicative figure of 20 Million US for the HSU system. This leaves about 42.3 Million US for items (i) solar field and (ii) heat collection, namely a target figure of 93.8 US/m^2 and 75.9 US/m^2 respectively for the N-S and E-W orientations.

The competitiveness of the solar plant with respect to fossil fuels is of course greatly enhanced by a more favourable location. For instance, in the case of a desert site (Albuquerque), the yearly averaged solar yield is increased by the factor 170/108 = 1.57 (see Figure 30), with an effective capital cost increased to $1.57 \times [62.3 \text{ Million $US]} = 97.1 \text{ Million $US}$. The target figure for the solar field and the heat collection becomes then the more favourable figure of 171 $\text{$US/m^2(N-S)}$.

Of course, all these figures — which are largely independent on the size of the plant since they are related only to the saving in fuel — refer to a large series production and not to the prototype.

³⁷ It may be possible to achieve a substantial cost reduction for such a huge quantity.

5.— The new advanced solar laboratory, LASA.

5.1. General considerations.

The development of the industrial scale prototype plant of 40 MWatt_e and the definition of solar hydrogen project require an extensive R & D activity in a



dedicated and easily accessible site. Therefore it has been decided to create a new ENEA laboratory (<u>Laboratorio Solare Avanzato</u>, LASA) presumably near Latina, at about 70 km from Rome, on an area previously dedicated to an experimental reactor CIRENE, which has never operated because of the nuclear moratorium in Italy. Other locations are also under consideration.

The general layout, described in more detail in Ref. [59], is shown in Figure 31. All conventional facilities (road, buildings, cooling, electrical substation, connection to the grid and so on) which were originally constructed for the 40 MWatt reactor can be re-deployed for the solar project. There is sufficient free land (> 12 ha) to install a \approx 40 MWatt peak solar parabolic troughs, corresponding to a time averaged electric power of 4 MWatt. Ample extra space remains available for an experimental field of dish mirrors for a future experimental plant for hydrogen production.

Orientation	E-W	N-S	
Number of collectors	114	96	
Total collectors area	6.30	5.31	x 10 ⁴ m ²
Collectors spacing	11.5	11.5	m
Solar field area	13.	11.	x 10 ⁴ m ²
Solar field peak power ³⁸	44.8	37.7	MWatt
Salt flow rate at peak power	112.7	94.9	kg/s
Distribution network length m	1100	1100	m
Solar energy on the collector plane	63.2	57.9	GWatth/y
Solar energy transferred to molten salt ³⁹	42.2	39.7	GWatth/y
Maximum deliverable power (30 d. average)	9.6	9.5	MWatt
Storage capacity	500.	500.	MWatth
Delivered thermal energy fraction	95.1	96.0	%
Delivered thermal energy	40.0	37.2	GWatth/y
Electric nominal power	4		MWatt
Thermoelectric efficiency at nominal power	39.9		%
Thermoelectric efficiency at 0.7 nominal p.	39.4		%
Thermoelectric efficiency at 0.3 nominal p	36.2		%
Condenser cooling flow rate	644		m ³ /h
Delivered electric energy	15.6	14.5	GWatth/y
Solar to electric efficiency ⁴⁰	24.7	25.0	%

Table 10. General parameters of the R & D installation in Latina

 $^{^{38}}$ At 900 W/m 2 and an efficiency of 79% (see Table 2).

³⁹ With an yearly average efficiency of 66.7%



The principal advantage of the Latina location for LASA is its vicinity to the main ENEA Laboratory of Casaccia; however, and this is its main disadvantage, at such a latitude (41° North) and because of the prevailing weather conditions, the use of the solar power is limited to the summer months. We believe that this is not necessarily a serious drawback for a *test* installation, for which frequent interventions, implying shut-downs, are required. They can be scheduled during the winter months. Performance of the development installation can be easily extrapolated to more favourable locations.

In addition a considerable amount of R & D has to be performed on the heat storage, coupled with the electricity generator. Some of these activities are better performed with the help of a natural gas heater, which will be added to the installation and which obviously can operate all year around.

Thermal solar electricity generation may have an interesting market for stand alone plants of relatively modest size, in the range $5 \div 10 \text{ MWatt}_{e}$, for instance in several of the islands of the Mediterranean sea and elsewhere, for which the population, and hence the energy demand peaks during the summer months. The LASA installation could therefore constitute also an interesting prototype for the development and the commercialisation of such a line of products.

⁴⁰ This figure doesn't include night time losses, thermal losses due to storage and collection network.



5.2. Performance of the plant.

The main parameters of the plant are given in Table 10, both for the N-S and E-W orientations. They however refer to a full yearly operation, which is, as already pointed out, a rather unlikely possibility. The general functional diagram is shown in Figure 32.

The preferred orientation for summer only operation is North-South. The performance of the plant is shown in Figure 33, in which the summer period (day 100 to day 250) has been selected as active operation period. The average solar power collected by the parabolic troughs during this period is acceptable, 221 Watt/m². The occupations area is about 11 ha, with a mirror spacing of 11.5 m. The modular structure of the solar field has been used in order to fit the required space in the most convenient way, in particular avoiding a channel which runs centrally over the site.

A HSU with a maximum storage capacity of 500 MWatth has been chosen. With such a storage capacity, the unscheduled operation is acceptably low.

The main parameters of the storage tanks, operated with the binary mixture 60% NaNO₃ and 40% KNO₃, are given in Table 11. The energy loss after 1 day is 0.34 %, corresponding to τ_c = 290 days.

	Hot tank	Cold tank	
Volume ⁴¹	2735	2602	m ³
Salt mass ⁴²	4528	4528	ton
Diameter	17.1	16.8	m
Height	12	11.8	m
Power loss ⁴³	102	71.5	kWatt
Nominal Salt temperature	550	290	°C
Salt Temperature (after 1 day)	548.7	289.1	°C
Salt Temperature (after 30 days)	512.9	264.5	°C
Energy loss (after 1 day)	2.5	1.7	MWatth
Energy loss (after 30 days)	71.3	49	MWatth

Table 11. Parameters of the tanks of the HSU.

5.3. Extrapolation to a sunnier location

As already pointed out the location of the LASA Laboratory is far from optimal from the point of view of solar yield. Its main purpose is to constitute a test bench for the method.

The plant is however also a useful prototype for modular installation in the $5 \div 10 \text{ MWatt}_{e}$ range. Therefore it is worth while to estimate the performance in a more favourable location. As previously, we take as a reference location the one of Albuquerque (US), which is typical for applications in the Southern part of the Mediterranean regions.

⁴¹ A free volume allowance of 5% for the hot storage container and 10% for the cold one.

⁴² The salt in the distribution network and in the steam generator is not included.

⁴³ Calculated for an outside temperature of 0°C.



In Figure 34, we give the yearly thermal energy delivery for the plant of Table 10 as a function of the HSU storage capacity. The electric energy delivery must be multiplied by the thermo-dynamical efficiency, ≈ 0.40 .

6. – Conclusions

The present report illustrates the strategy that ENEA intends to follow in order to further develop the concept of thermal solar energy. Such a strategy is directed toward two main lines:

i) *High temperature (550 °C) heat production and storage* for industrial applications, as a substitute to fossil fuels at a competitive price. In order to achieve such a goal, many of the features now considered for Solar Towers, namely a high temperature, mirror manufacturing techniques and an extensive storage based on a molten salt of low environmental impact and low cost have been embodied in the more conservative and rather well developed linear trough modular geometry. We believe that this combinations is suited best for the kind of locations of our potential interest.

In order to do so, one has to generalise the use of mineral salt circulation to the solar field, overcoming the problem of salt freezing which occurs at a relatively high temperature of about 220 °C with the use of an appropriate over-night procedure (and eventually the use of "night-caps") and with a flexible electric heating system which makes use of the relatively high resistivity of the steel in order to re-





Figure 36. Current prices of bulk electricity production, without subsidies and excise tax in the major European countries (source: EU Green book on Energy Supply).

heat collecting tube in case of a freeze-out. In addition, the tube coating has to be optimised to the different in spectrum of the reemitted infrared light. We believe that with an appropriate R &D it would be possible to achieve such goals.

As result of such changes, we believe that the cost of energy produced with parabolic trough should approach the one forecasted for Solar Power Towers, for instance according the extrapolation curve of the US-Department of Energy (Figure 35), with the added advantage of removing the need of very tall Solar Power Towers (of height comparable to the solar field radius) and of a precise focussing of sun's light to long distances. These prices compare well with those for other renewable energy sources, as shown in Figure 36. Note the much higher price of the photo-voltaic option.

One must reconcile as well the steady availability requirement of any industrially based mature application with the intrinsic variability of the solar energy, with the help of an intermediate energy storage of adequate capacity and duration. Amongst the types of renewable energies (Figure 36), both Wind and Photo-voltaic are generally plagued by the substantial variability and fluctuations of the availability of the solar resource, which must be overcome "off-line" and at an extra cost, with the help of an *electric* energy storage of the types illustrated in Section 1.6 and in Table 1. Instead the solar thermal option permits to store directly and efficiently high temperature *heat* in a easily reversible process. The extended use of

such a thermal storage permits a much more efficient use of the subsequent facilities (electricity generation) – which must be sized to match the average rather than the peak power. The corresponding saving in their costs (more than a factor three in the installed power) largely compensates the expense for an added storage system. The added possibility of scheduling the power delivery according to the requirements of the market, rather than according to the variability of the solar yield, represents an other important, added asset. For these reasons, the development of an extended thermal energy storage constitutes one of the main strategic choices in the ENEA programme.

Direct Hydrogen production by solar dissociation of water. ii) This programme, of considerable strategic interest, is still in the initial R & D phase, but it will undoubtedly require temperatures which largely exceed the ones possible with parabolic troughs. Hence collectors of a full parabolic profile are necessary. With this technology, as well known, remarkably high temperatures can be achieved, in correspondence with very large concentration factors. The choice of the specific method will be performed taking into account (a) an acceptably high solar to hydrogen conversion efficiency, which is presently targeted to about 50%; (b) a chemical cycle which could be operated in a plant sufficiently simple and easy to operate to be placed in a relatively isolated solar field (c) use of chemical substances of low environmental impact, not toxic and abundantly available at a low cost. In these perspective scenarios, two possible operating temperatures emerge: some cycles, like for instance the UT-3, which require heat collection and storage and a temperature in the order of 1000 °C and other, more exotic schemes of Redox of metals for which the temperature is much higher, of the order of 2000 °C, but not yet prohibitive from the point of view of re-radiation from a cavity collector. These last devices should be much smaller, directly located in the focal point of a single parabolic mirror, with the sunlight heating directly the chemical compound and therefore without an energy storage. Again, the most relevant parameter in the success of the programme is the one of producing hydrogen at a competitive market price, which we set in the range of $5 \div 10 \text{ US}/\text{GJ}$. There is no doubt that eventually the advent of the fuel cells, for which the ideal fuel is hydrogen, will spur the demand for such a product. In this respect, the high conversion efficiency in electricity of fuel cells, for which projections exist of up to 70 ÷ 80 %, associated to the "zero" emission feature of the combination solar hydrogen + fuel cell, may constitute an important incentive.

The ENEA strategy, to be deployed in direct collaboration with industry, will therefore proceed initially along three different, parallel lines:

- A strong R&D programme in the few elements of the parabolic trough, which are required by the variants introduced, and on the choice of the best reactions for hydrogen production.
- The realisation of a ≈ 4 MWatt_e (continuous) demostration power plant with parabolic troughs in a non optimal, but practical location, as a prototype for a market niche in the 5 ÷ 10 MWatt_e production, presumably not to be connected to a large grid.
- The (subsequent) realisation of one of more 40 MWatt_e (continuous) demonstration power plant modules with parabolic troughs in sunny location in the south of Italy, destined to power production for the national electricity grid, as a prototype for large scale applications, which may include also the possibility of extending many existing industrial technologies (like for instance thermal electricity generation, gasification of carbonaceous materials to form synthesis gas, thermal cracking of low hydrocarbons to produce important basic materials, endothermic industrial reactions, etc.) to the solar, "zero emission" option.

In the case of the parabolic troughs in a southerly Italian location, and as already discussed in Section 4.7, in order to become competitive to a cost of fuel (natural gas) of 5.5 (GJ, the capital servicing for the solar field must meet the target figure of 93.8 US/m².

Such a competitiveness of the solar plant with respect to fossil fuels is considerably enhanced in a more favourable location. For instance, in the case of an optimal site, where the yearly averaged solar yield is increased by the factor 1.57 (see Figure 30), the target figure becomes 171 \$US/m².

Of course, all these figures — which are largely independent on the size of the plant since they are related only to the saving in fuel costs — refer to a large series production and not to the prototype.

7. – List of contributors

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