Global perspective on solar energy and imperatives for India taking the global leadership: A technology perspective with focus on India's energy needs

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Abstract | Solar energy is poised for big developments across the globe and the next decade will see several technological breakthroughs to make solar a viable option. In emerging economies like India and China, growing demand for energy, dwindling resources of fossil fuels and climate change challenges will make solar an inevitable option. A tropical country like India with abundant solar radiations is rightly poised to take a global leadership in this field. The paper gives a detailed account on the various options for exploration of solar energy including solar photovoltaic and solar thermal. The paper also focuses on importance of distributed energy generation as well as combined heat, power and cold energy cycles. A three pronged comprehensive strategy for solar is presented along with need for building direct conversion of solar energy into cooling/heating/desalination applications. Importance of building manufacturing clusters for components which are critical to solar technologies across the country is also emphasized in the paper.

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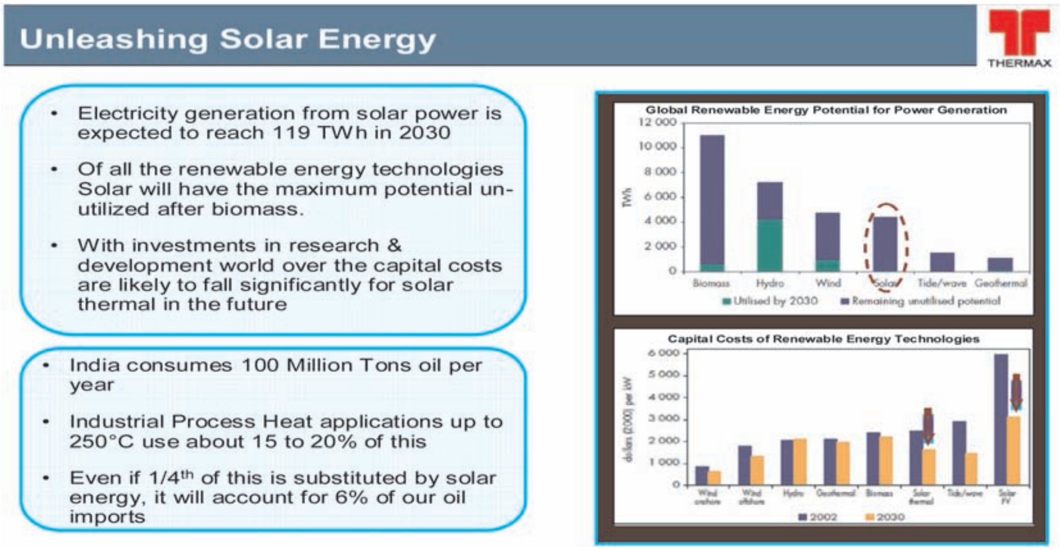
Introduction

The glorious years of Indian civilization which were rich, vibrant, embedded in simplicity, and used the elements of nature as the very philosophy of life have had their downturn in the past two hundred years of industrialization. A country which was a proud global leader in art and trade till the sixteenth century – it is indeed tragic that India is labeled as an agrarian society while the truth is that India is much more than that given the vast diversity in art and culture- missed the excitement of the industrial renaissance. In the last twenty odd years, India has been catching up in science and technology, but is still far away from assuming any global leadership role.

China has become a global workshop, the US is concerned about its declining eminence in science and doing everything to regain the number one position in technology, while Europe is pushing its strength in high quality manpower for building its dominance. India's levers for regaining its glory are a bit of the above three *viz.* the low cost manufacturing competence of China, the eminence in science of US and the evolving intellectual capital of Europe. The challenge in all these is India's energy security concerns and the sustainability of its growth pattern which is absolutely essential if India has to assume a global leadership position. This is where solar energy plays a major decisive role.

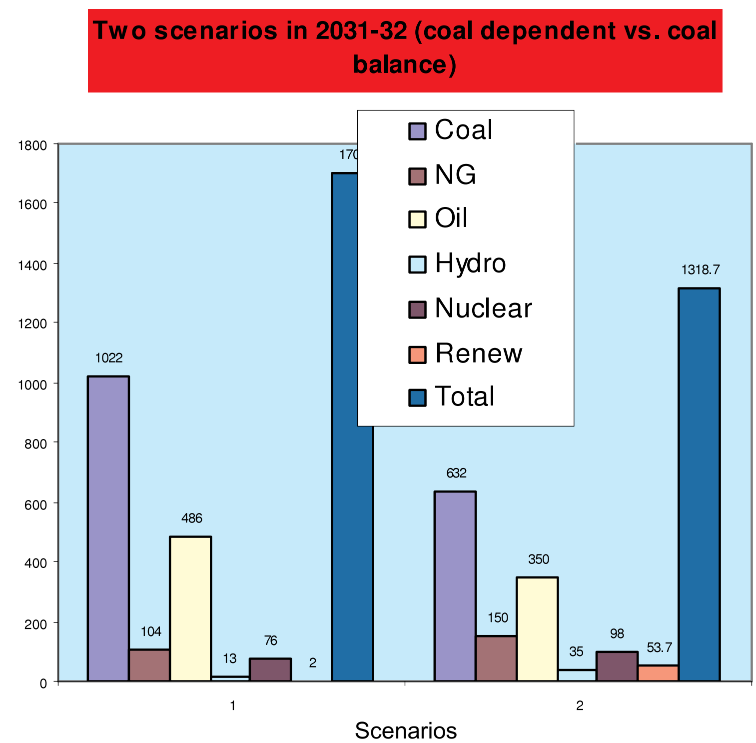
Solar energy as an alternate energy resource, therefore, fits India's bill more than anything else. The ever growing demand for energy in India, combined with dwindling resources and the threat

Figure 1: Potential of solar energy globally and India's position.



of climate change, makes solar energy a perfect alternative. That India should push all the resources at its command and become a world leader in this field is obvious. The Solar Mission unveiled by the prime minister of India on 11th Jan. 2010 is an indicator of the highest level of commitment for the same.

Figure 2: Two scenarios of energy demands (coal dependent vs coal balance). Ref: Integrated Energy Policy- Planning Commission report 2006.



To become a global leader, India should have a credible technology base and manufacturing capabilities across the complete solar energy spectrum. This paper deals with a few critical aspects on the road map that India should follow to assume such leadership. Technology development and deployment (TDD) strategies matched with progressive, innovative policies and ancillary manufacturing clusters can make this happen. The world can then look to India to provide inspiration and leadership. India might have missed many scientific revolutions but can hardly afford to miss this one. Destiny beckons us to take the plunge and this paper provides imperatives and a road map towards that goal.

Energy needs of India

India is growing at nearly double digit levels and it is imperative that we maintain this momentum for the next two decades. This is a challenge and the one critical issue which can upset the development trajectory is the availability of cheap, reliable and bountiful energy. The needs of energy are across all the spectrum of energy demand – the electric, thermal and transport sectors.

Integrated energy policy

By the year 2031–32, India will be consuming 1756 million tonnes of oil equivalent (MTOE) per year

(India then, would still be at a global average number in terms of per capita consumption) of which about 486 MTOE will be in the form of oil and gas. This would be about eight to nine times India's domestic production capacity making India highly vulnerable to geopolitics. Coal is yet another commodity India can still depend on but the country will have to face the global consequence of use of coal in large scale (about 2 billion tones of coal or 850 MTOE) and the way the climate dialog will progress. The alternate appears to be nuclear and solar energy. The rest of the renewable energy resources like hydro, wind and biomass will be peripheral; it will be solar enery which can be a credible alternate clean energy source. Nuclear is a good option but fraught with a few aspects like safety and accessibility to undesirable elements. Besides, the future needs of energy will be inclined towards the distributed mode – "Generate where required" paradigm will certainly make nuclear energy a second choice.

The two scenarios presented by the planning commission a based on *coal dependent* and *coal balance* scenarios. The coal dependent scenario refers to a scenario which uses coal as a major energy supplier while the second scenario is described as a '*best-case*-scenario' where the other energy options including the maximizing energy conservation programme (taken up as one of the climate change missions by the Government of India) and other energy sources are optimized. **The per capita energy consumption is kept at the same level but with improved energy intensity numbers.**

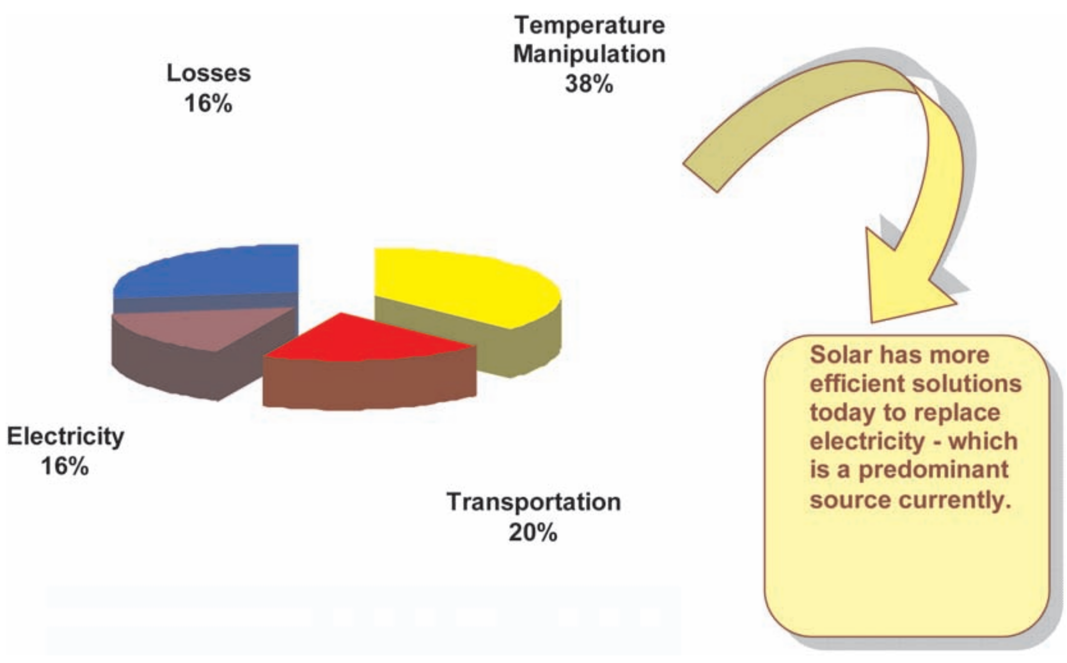
Energy needs are not only in the form of electricity but are all pervasive. The needs of energy are for domestic, industrial, lighting and transport sectors. There is an entire band of energy used in industrial and consumer sectors where energy is used for heating, cooling (and drying, desalination etc.) which is not dependent only on electricity as a primary energy source. Besides, in India, 20% of energy is used as non-commercial energy in the rural sector where energy demands are greater for cooking and lighting needs. (Ref. 8 – Integrated Energy Policy, Planning commission report).

Thus, a whopping 38% of energy is needed for what we call temperature manipulation where we need energy at different temperature levels.

Energy sources

India's poor energy resource base is clearly a major cause for concern. Apart from coal, India has poor hydrocarbon (oil and gas), weak uranium resources and limited hydro potential (~150 GW). As explained in the text box adjoining Fig. 2, India has to push hard on renewable energy sources as credible alternative energy supply systems. When compared with other renewable energy sources, solar energy stands out as a clear winner. The following table exemplifies it in a more fundamental way using photon to energy conversion mechanisms.

Figure 3: Energy usage pattern (Ref. World Energy Outlook).



Efficiency of photo synthesis:

∗ Light absorbed (400–700 nm)	43% of incident solar radiation
∗ Approx. 8 photons required to fix one molecule of CO_2	
∗ Conversion of absorbed radiations	80%
∗ Respiration requirements	33%
∗ Overall theoretical efficiency	11 to 13 %
∗ Actual efficiency	0.1–2.0 %*

Up to 8% efficiency is reported but practically, 0.1 to 2.0% is observed.

Solar direct energy conversion at 10% in PV and 16% in CSP is several times higher than the above route. Hence sustainability of solar energy is more in direct conversion systems.

This explains, fundamentally, why biomass, whose primary source of energy is solar, is much less efficient compared to direct solar energy conversion devices. Every index of energy conversion including the need for water and land indicate that solar energy is clearly the most attractive form of renewable energy.

Solar energy technologies

Solar energy can thus be made all-pervasive meeting various energy requirements ranging from electricity, temperature manipulations and transport (see fig. 3). Solar energy can be a typical large sized grid or a smaller-sized down stream grid connected or distributed in an off-grid mode. About 93.8% of current solar energy is used in the form of direct thermal energy mode while about 5.9% is used in the form of electricity being generated by solar PV. 0.3% is used as concentrated solar thermal to power generation mode. The current global solar energy scenario shows that major generation from solar thermal energy is used mainly for heating applications in low to medium temperature ranges (normally between 80 to 120 deg C). The total solar energy generation globally today is 146.8 GW (th) with only about 9 GW in the form of electricity. The current solar energy forms less than 1% of the total energy demand of the globe and herein lies the challenge – How do we jump from 1% of installed capacity to 20% of installed capacity in the next two decades so that at least 5-10% of energy consumed will be solar? This is a big challenge. How we attain this is a paramount question in the minds of technocrats, academicians, policy makers and politicians. What are the technologies, how are we going to deploy them, where are the competencies and how are we going to build a sustainable model? There are also more questions on how we make solar energy a credible and viable alternative given its uncertain availability which is subject to micro climatic conditions. There are many issues involved in making solar energy a 24 × 7 option. What are the storage options? The Integration of solar power into the existing grid is another question that will haunt us at yet another level. Hence, making solar energy a reliable and cheap alternative source requires a very different mechanism which is probably without precedence at the global level. Whether the cost of solar energy will be viable, how far sovereign governments can support this initiative, and what mechanisms are to be put in place are some of the major issues where the debate takes place. The discussions below try to address some of these questions particularly applied to the Indian situation.

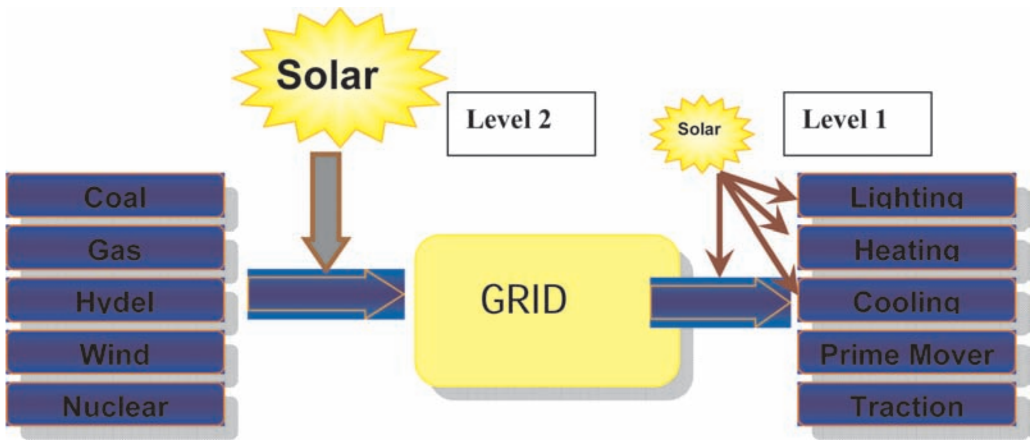
Let's formulate our discussion on two levels. Level one is solar energy used directly for end applications or energy generated in a distributed mode-based generation device which is the most feasible way to exploit solar energy. Level two is where solar energy is used to generate utility size power generating stations or large sized industrial captive power plants – typically 10 MW to 100 + MW sized plants.

Level 1 Solar energy for end application devices

The applications here are energy for lighting, heating, cooling applications for domestic and commercial sectors, MSME sectors (micro, small and medium scale industrial sectors), energy demands for cooking sectors and finally solar energy for transport sector applications. The demands above are also met by utility grade power plants. The basic question is which mode of energy will be the best mode for the given applications.

At this junction, the solar energy debate goes further with solar PV and solar thermal as two options available to exploit solar energy. Solar thermal energy conversions are those devices which convert photon flux into heat which, in turn, is converted into electricity. Heat can also be used directly for many other applications while solar PV converts solar energy into electricity in a more elegant and simple way. Thus, if the end-application is electricity needed for lighting and driving motors, then both PV and solar thermal can be used but PV has a definite edge over solar thermal due to the simplicity of its energy conversion device. And if the end application is for heating, cooling, and such other applications (where electricity can also be used), then a thorough thermodynamic analysis and techno-economic analysis will be required for the selection of best the mode of energy use. For combined applications, solar thermal energy becomes an obvious choice.

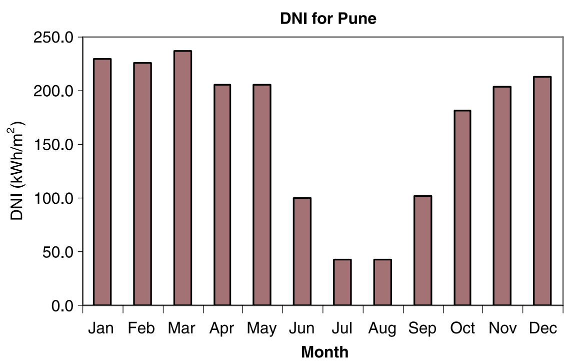
Figure 4: Level 1 & 2 solar energy technologies.



Photovoltaic solar energy

The solid state semi conductor driven electricity generation based on the photoelectric effect is a well studied subject and this paper will not dwell on this. The photon to electron conversion mechanism is well known and the theoretical efficiency levels and losses have also been well studied. The constant debate going on between crystalline Si based PV and thin films based on amorphous Si and CD/TE/CIGS is enriched by the improvements in efficiencies and reduction in the quantity of semi conductor materials (thinner sections). The target on efficiencies is rising while the costs are shrinking. All-round improvements in the form of lower costs of raw materials (changing from electronic grade to metallurgical grade UMG grade), and the process of deposition, multi junction systems, thin films in CdTe, grating of incoming radiations, modification in the spectrum to get the close band gap matching are showing results in making the system less expensive and more efficient. The developments in solar PV are happening at a rapid pace- even defying the Moore's law. The cost of cells has come down dramatically and the current trends indicate that future costs will be less than 1.5$ peak watt (Wp) with the balance of system costs included. Peak watt analysis at ISO conditions of 25 deg C can sometime cause distortions in the actual energy costs. For example, a peak watt PV can generate 4.8 watt hr per day (Wh/d) in a solar rich area (in India this is true only in areas like parts of Rajasthan and Ladakh).

In the rest of India (DNI for Pune and daily IBN are shown in the two graphs below), the situation is less promising with a peak watt generating only 3.6 Wh/d (assuming three months of monsoon). For a 25-year life of PV (assuming no degradation), we can generate 43.8 kWh/or an entire cycle in a solar rich area or 32.4 kWh/entire cycle in a solar average area. Further, taking into consideration losses in the power control system (inverter and power transmission) and also degradation over a life cycle of 25 years, 1 Wp gives 80% of the life cycle electricity generation which means 35 kWh



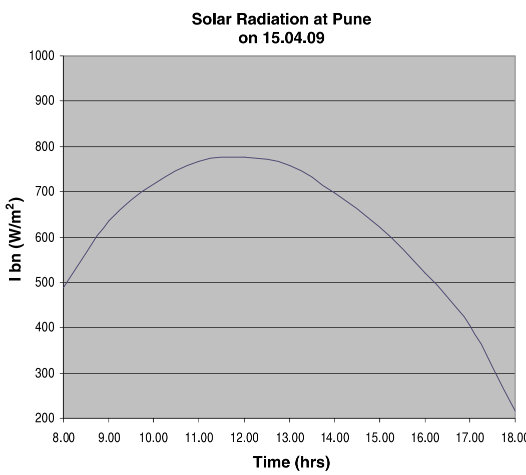


Figure 5: Global incentive framework.

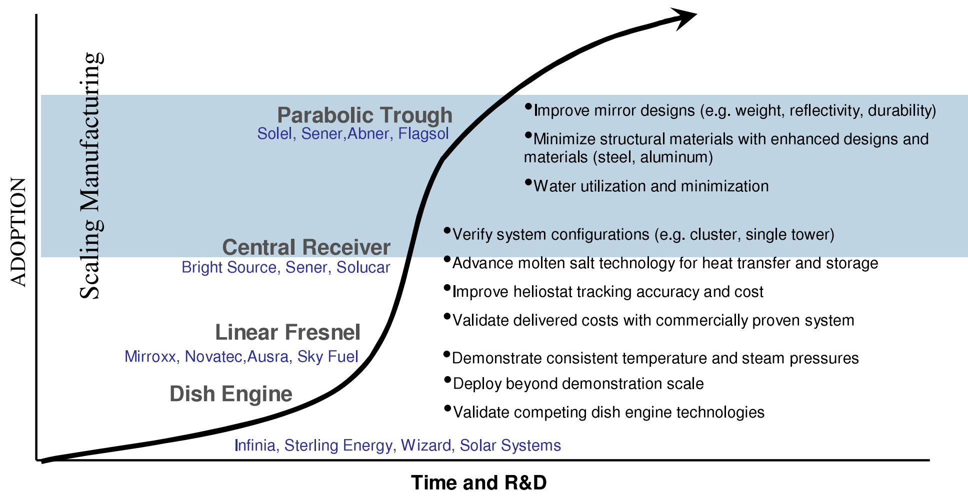
and 25 kWh for solar rich and solar average areas respectively. If the cost of electricity is pegged at a generation cost of 4.5 Rs/kWh, this would mean that the capital cost of PV is less than 157.5 Rs per Wp (~3 $/Wp) for a solar rich and 112.5 (~2.25 $/Wp) for a solar average area. This cost does not include financing and other O&M costs but gives approximate numbers to understand the real of cost of solar PV. The financing costs and other O&M costs (another 50% escalation on these numbers) would make the cost of PV power difficult totally with the grid parity costs. The generation-based incentives (GBI) rise from the premise that future cost projections will enable solar power to become grid parity power when fossil-based grid power starts escalating. The cost of peak watt PV would be between 2.5 to 3.5 $ and this can be used for cost comparisons with other solar energy conversion devices as well as direct energy conversion systems. The wide variation in solar radiation imposes a penalty on the cost of the peak watt cell.

A Solar PV set up in Ladakh (solar rich) compared to one in Pune (solar average) would demand a cost reduction of PV from Rs 157.5 to Rs 112.5 for a 1 Wp solar cell to match the cost of electricity generated from solar energy. Thus the PV to be set up in areas like the deserts of Rajasthan to moderate solar radiation places like Bangalore will have an impact on the cost of the cell or the cost of electricity generated. These issues need to be debated when we speak of PV based systems. Hence increasing the member solar PV-based systems will necessarily be dependent on government subsidies in order to make them viable. There are many questions on the nature of subsidies and the period till the subsidy may have to continue.

Solar thermal energy

Solar thermal energy is based on the optical conversion of incoming radiation into heat, and then making use of the heat in other energy conversion devices. As the case of solar PV, efficiency is a major concern in this case also. However, unlike in solar PVs, optical radiation to thermal energy conversion is much more efficient due to the very nature of the conversion process. As high as 60–70% efficiency can be achieved from photon flux to heat flux. Subsequently, the heat flux can be used for electricity generation or a combined cycle of electricity and other forms of energy. The downstream conversion of heat into energy is classical in nature with a fairly wide knowledge base in India. In terms of numbers, energy conversion devices sourced from insolent radiation to final forms of energy can range from 16% to 29% which exceeds the current PV conversion efficiencies.

Figure 6: Recent developments in solar thermal.



Concentrating the photon flux in an efficient and cost effective manner is clearly a challenge and there are number of devices which are available. The developments take place in the same way as PV devices viz. they increase efficiency and reduce costs. The developments in these areas are also as exciting as PV and innovations happen continuously.

Some of the developments in solar thermal energy are shown in Fig. 6. The major challenge here is to optimize the temperature and optical-cum-thermal efficiency in the solar collector-cum-receiver system; a detailed analysis is out of the scope of this paper. But, it is clear that if we want to combine efficiency with the cost of the system, new avenues open up which are crucial for medium solar radiation locations (600–750 peak watt/m^2 zones). The incoming solar radiation (say 750 watts/m2) goes through three to four different devices before it is captured thermally. Each device causes a loss in the flux and these needs to be carefully considered for evaluating the process systems in an integrated way. The collectors of this energy lose specular radiation in the form of absorption and dispersion, while a glass tube (in the case of a linear receiver) or a cover glass plate (in the case of a point receiver) lose energy by reflection and absorption. Finally, the receiver tube loses some fraction of energy through reflection in the optical spectrum. Once the energy is converted into heat, there are losses by infrared radiation from the heat transfer fluid to the receiver surface, and to the surroundings. Thus, combined optical and radiative heat loss indicates that optical efficiency is a function of incoming radiation flux and various optical parameters. Convective losses additionally act to convert optical efficiency to thermal efficiency. Some analyses carried out indicate that optimum results are obtained at medium temperature levels (normally between 220–150 deg C).

Figure 7 summarizes the analysis carried out for one such location where a solar thermal power plant is being built as a distributed generation system.

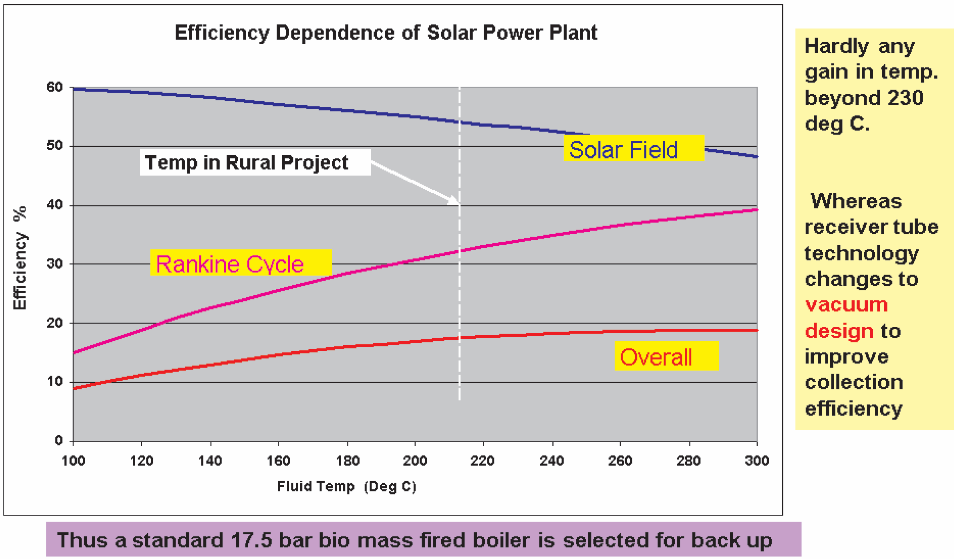
High conversion efficiency can be achieved if heat is used for cooling/heating or even thermal desalination purposes. The overall conversion achieved using vapor absorption cycle can be as high as 37.1% even at medium temperature applications which will be perhaps be the highest any device in solar energy can be designed for.

The temperature is a strong function of the efficiency and cost of the system. While remaining in a non-evacuated space for the receiver tube due to the costs involved in the design, it is felt that 220 deg C could be one target temperature which can be effectively used to convert solar radiation into heat which can then be integrated into combined power, heating and cooling applications in the most optimal way. The efficiency achieved is as follows in Fig. 8.

Thus, wherever energy needs are not purely electrical (which is true in most cases) one should look for an integrated power and combined cycle through the thermal route as per the discussions given above. Pure electricity generation or small scale (less than 5 kW) generation is based on PV systems in the same way that the hot water needs of a domestic unit are based on flat plate (evacuated tube) roof top systems.

Arising out of the discussions above, an interesting application given below needs careful

Figure 7: Optimum solar thermal temperature.



investigation. This is the case of cooling applications. India uses approximately 29% of the electricity generated for cooling applications. These range from industrial space cooling (lowest quality cooling) to comfort cooling to cold storage and process cooling applications. About 34,000 MW of electricity is used, and at the generation level, another 20% excess is needed for taking care of transmission and distribution losses. The option which is available is on-site generation of cooling without using wired power. Two options arise:

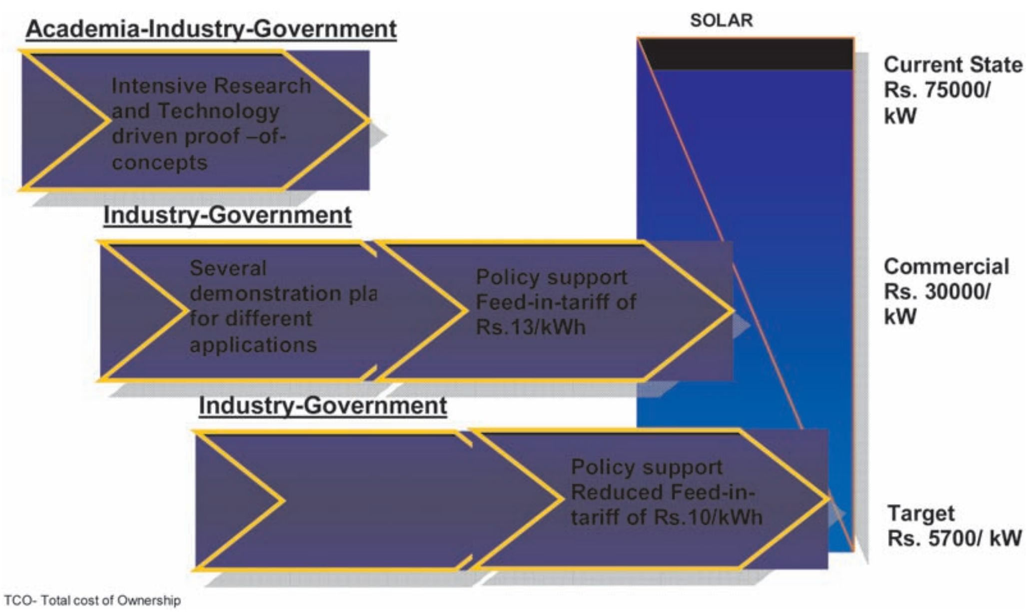
1. Generate on-site power and run the compression based cooling system.
2. Generate on-site heat and run an absorption based heat pump for the cooling system. A fundamental analysis shows that for 1 kW comfort cooling (16 deg inlet air cooling – 7/12 deg chilled water or direct refrigerant), the electricity needed is 0.33 kW (COP of 3 under air cooled system). With an overall efficiency of 10% PV, a 3.3 kW solar PV panel will be required to meet the 1 kW cooling demands. The Cost of such a system would be (150 Rs peak watt and corrected for an average radiation of 700 W/m^2 and averaging on a daily basis) approximately Rs 1.35 lacs for the solar field, assuming it operates only during solar time. (If an extended period of operation is to be met, then costs will go up proportionately to meet the needs of increased generation and also storage in the form of battery systems). The other option is an absorption based system. 1 kW comfort cooling (16 deg inlet air – 7/12 chilled water or direct refrigerant) can be obtained by a highly efficient absorption system under an air cooled system which would require about 0.9 kW of thermal load. With an overall efficiency of 62% thermal, a 1.5 kW solar (concentrated solar) panel will be required. The Cost would be Rs. 0.5 lacs only for the solar field. The integrated cost of the solar field (PV or CS thermal) with the cooling engine will favour the thermal route at the current developmental level.

Figure 8: Efficiency and other parameters for different power cycles.

	Steam Only	ORC	VAM
Power	256 kW	256kW	256 kW+160TR
Efficiency	8.1%	12.3%	37.1%
Solar Field (m^2)	6500	4500	6500
Land (Acre)	3.76	2.67	3.76

The discussions thus indicate that the choice of PV and Thermal are indeed based on end-application needs and cannot be solely dependent on the cost of electricity. Though the simplified analysis above indicates the importance of direct

Figure 9: Road map for making solar cooling a viable option.



generation of final energy needs through an on-site generation system, it will require radically different policy support to match the current feed-in-tariff system available for big-sized electricity driven solar power plants. A summary of what is needed is illustrated in the figure 9. The target figure is to match the solar based cooling device with that of current electricity-driven systems where electricity is generated at a distant location – solar or fossil based – to an on-site generation system. If the solar power at a distant location gets a liberal feed-in-tariff (14.5–16.9 Rs/kWh), it stands to reason that a much lower generation based incentive can make such cooling systems highly attractive.

This calls for creating incentives for the virtual power which would have been consumed in generating each kW of cooling. This incentives necessary for virtual power are much lower than the current GBI (generation based incentive) proposed for solar power. This, therefore, makes more sense.

The local generation of cooling through PV or thermal energy can be left to modern methods which are evolving rapidly. The market will select the best combination of technologies, once the policy framework is in place. In the current scenario there is a tilt towards CSP based cooling rather than PV, but ongoing developments in PV can tilt the balance in its favour. In this context, a combination of PV and CSP, i.e. concentrated PV, can bridge these two technologies and may perhaps prevail. The discussion on CPV is excluded from this discussion due to the space constraints.

Level 2

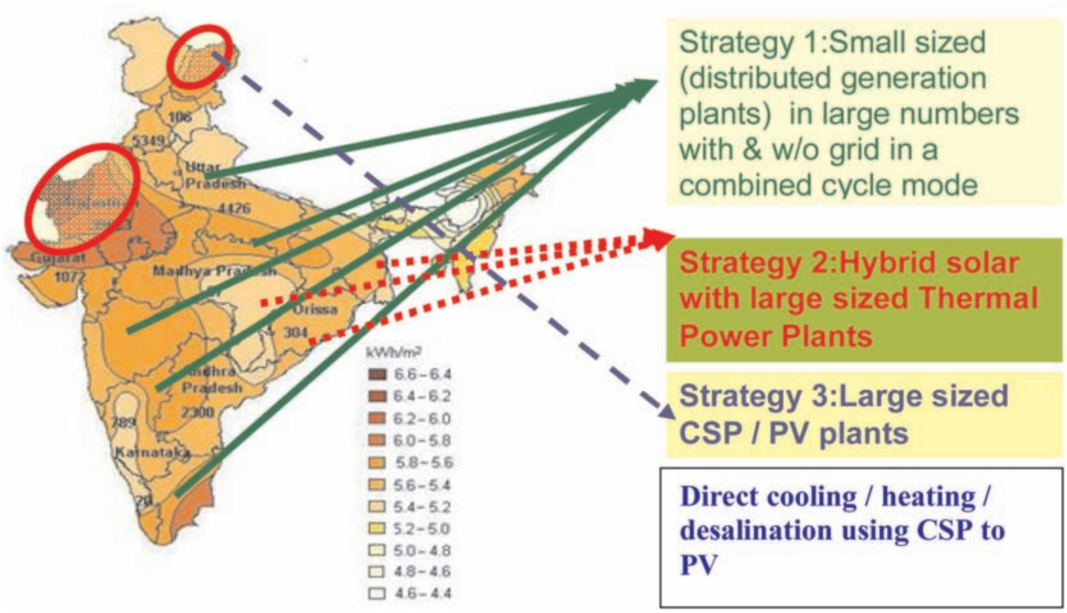
The large scale power generation system is yet another major challenge in solar energy. As mentioned, the distributed solar combined cycle appears the best option from cost and efficiency considerations, these demand a favourable combination of power and other uses of energy which may not be possible in large scale generation stations. Therefore, the large-scale generating stations (by our definition for solar it could be anywhere above 10 MW) will demand higher power generating efficiency either through higher temperatures or through the dovetailing of Organic or Kalina cycles. The design of such plants needs careful investigations of solar insolent radiation, solar optics, receivers and power plant cycles. Several innovative designs can be considered not discussed within the scope of the current paper. Again, CSP appears a better option though improved tracking controlled PV cannot be left out of the discussions.

Based on the broad discussions above, the following strategy appears best for India given its diversity of energy needs as well as varying solar radiation.

The figure 10 summarizes this in a succinct way.

This has been done using a very pragmatic understanding of India's energy needs, insolent solar radiation pattern and sustainable model for both urban (economically strong) and rural (economically weak) settings. For a detailed analysis, please refer to the author's presentation to the Solar Mission.

Figure 10: India centric solar strategy.



A few critical aspects on solar energy

Plant load factor is an important aspect in the design of solar energy systems. The storage of solar energy either in a thermal form or electrical form is being debated in the current emerging scientific and technological literature. This is still an evolving topic. The author feels it is best to develop solar energy based on hybrid versions (strategy 1, 2) viz. use agro waste / biomass or big-sized fossil-based power plants where a solar panel integrated with the bottom portion from condenser water all the way to the economizer could be one of the best choices for the exploitation of solar energy. Even grids can be considered storage systems (till solar penetration becomes formidable) and a good grid interactive system will obviate storage requirements. The issue is of critical importance for option 3 – large sized plants – since it raises considerations of making such plants operate continuously (24 × 7). Any other way would cause tremendous stress on the system, especially rotating parts like turbines, if they are operated only during solar time. Hence, a low cost high thermal inertia-based accumulator design will be necessary. Some of the current research trends of using concrete and steel and other ceramics are pointers towards such developments.

For stand-alone direct energy conversion devices like medium temperature heating and cooling systems, the developments in phase change materials show quite promising options of energy storage at the generation stage or at the cooling end.

A comprehensive analysis carried out at one of the sites indicates the varying nature of energy conversion devices and this is depicted in the figure 11.

In a typical setting (Shive village solar thermal power plant), the variation on a daily basis and over a twelve month period shown in Fig. 11 depicts the difficulties in the design of a 24 × 7 solar plant. This calls for an optimum name plate capacity, design of accumulators and storage etc.

All-pervasive solar

Solar energy for the transport sector will call for the generation of fuels from solar energy. Solar to fuels (STF) is a fast developing science and a tremendous impetus is being given to developments in this area. The use of bio-mimetic materials, plant photosynthesis systems using antenna-like molecular systems, and catalysis of photon to electron transfer processes are cutting-edge scientific work which can make a fundamental contribution to the use of solar energy in future.

Equally interesting is the high temperature thermal – solar furnace where solar energy is concentrated at 1000 plus suns. This can generate high temperature systems which can be utilized for thermo-chemically splitting water using many combination chemicals. Iodine – sulphur is one such where solar energy can generate hydrogen and can be made into fuel for transport applications using on-board fuel cell systems. This can generate energy for traction or power for driving hybrid vehicles.

Figure 11: Time integrated heat flux generation at Shive Solar Thermal Power Plant.

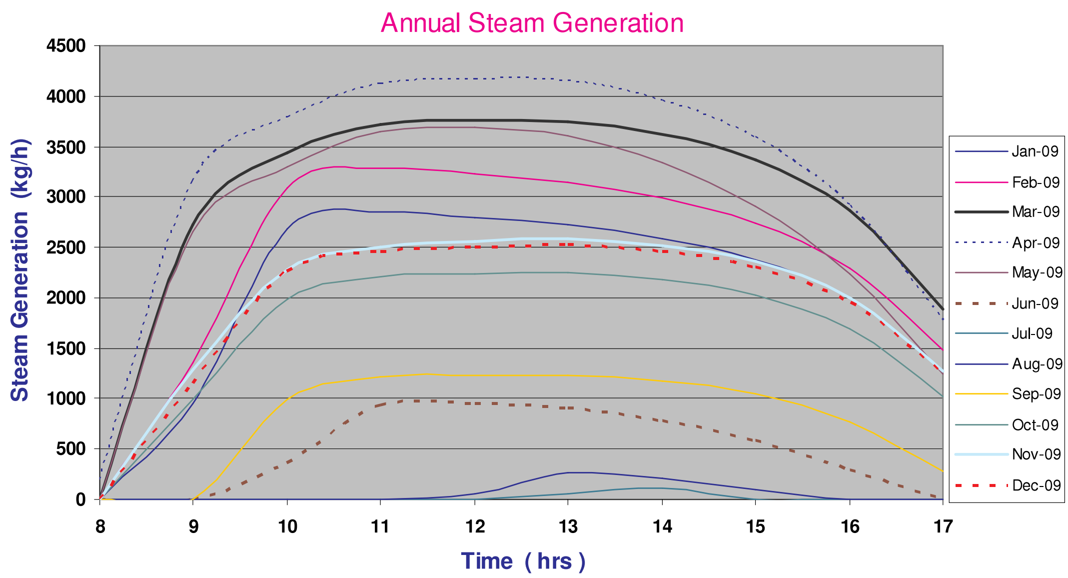
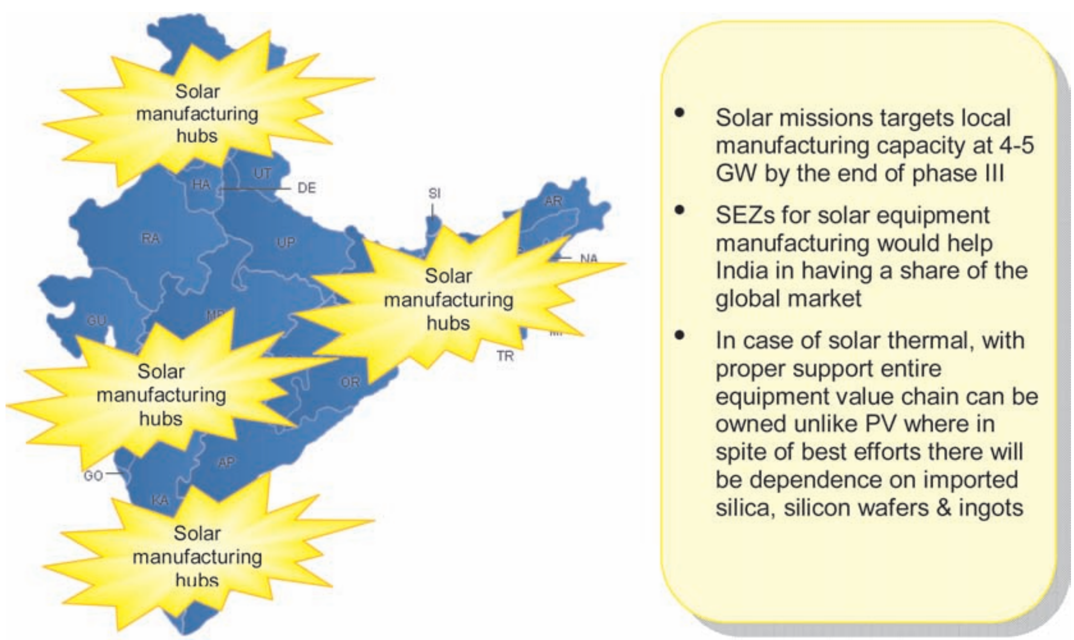


Figure 12: Solar manufacturing hubs in India.



Concluding remarks

Solar energy needs to be all-pervading. There are critical developments which are necessary for solar establishing energy in India. Two factors which need to be kept in mind are the cost and sustainability of solar systems. The three-pronged strategy suggested above could be one strategy which could enable the faster development of solar energy in India. Costs and sustainability arise when the large scale manufacturing of various components can be taken up within the country. We need a large number of manufacturing hubs, and towards this, CSP fits the bill more conveniently than PV due to the very nature of its components. Fig. 12 gives one such attempt to make solar energy all-pervasive in India.

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Prior to joining Thermax, he was in a senior management position in one of the leading power utility NTPC Ltd. in India and was heading their Technology Development Division. He was largely responsible for development of clean coal technologies and energy efficient systems for the Indian power sector. Dr. Sonde joined as Scientists in the Department of Atomic Energy and rose to become Senior Scientists in the department and was holding very senior positions in various capacities.

Dr. Sonde continues to serve as Member of the Senate Committee of IIT, Delhi; Member, Scientific Advisory Committee, Department of Science & Technology; Member of the Environment Committee – Department of Bio Technology. He is also Fellow, Indian National Academy of Engineering and member of its Governing Council.

Dr. Sonde was awarded the Dr. Homi Bhabha Gold Medal during the Golden Jubilee celebrations of BARC in the year 2006 by Hon"able Prime Minister for his outstanding contribution in the nuclear field. Dr. Sonde is also the recipient of Dr. Doraswami IIChE Medal and Gold Medal from the Indian Nuclear Society for his outstanding contribution in the field of Nuclear Science & Technology. For his academic excellence, he was awarded the Vishweswarayya Gold Medal for standing first in the University of Mysore.