Imperatives for combined energy generating devices for enhancing fossil fuel resource and integration with renewable energy resource for a seamless transition from fossil to renewable energy resources: Concept of virtual power

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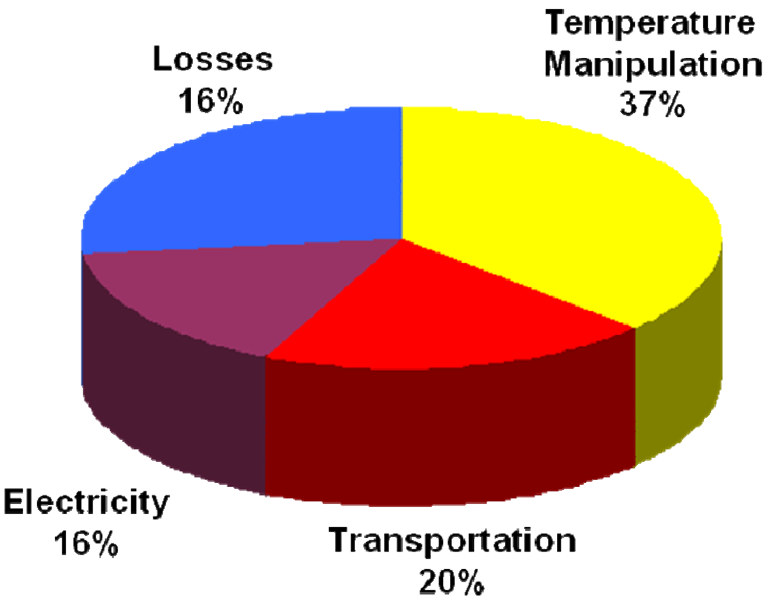
Abstract

A clear differentiation is seen on total energy consumption when compared between electricity and non electricity based applications. Very often for industrial, commercial applications non electricity demands are more than electricity demands. This is the key driver for transiting from electricity centric generation systems to poly generation systems. Further, there is a global trend to replace fossil fuels with renewable energy sources and nations are supporting this transition through various policy instruments like feed-in-tariff (FIT) or generation based incentives (GBI). All such schemes are heavily skewed towards electricity generation at the cost of non electrical energy. A concept of "Virtual Power" is introduced to address this anomaly. It is also illustrated how thermal technologies can be ingeniously utilized to optimize energy consumptions.

Keywords: Pinch technology, resource optimization, feed-in-tariff, generation based incentives, COP, virtual power, temperature approach, Sterling engine, Thermo electric devices, topping cycle

1. Introduction

Energy consumption in different parts of the society shows a clear pattern for electricity and non electricity applications. It is indeed amazing to know that non electricity demand (or demand of those applications where primary energy source could have been applied in more efficient way than use of electricity driven applications), far outweigh electricity driven demand of energy. For energy use demand pattern, sixteen percentage of energy is in the form of electricity while more than 28% of energy is for direct applications which are principally in the nature of "temperature manipulative applications" from sub ambient to positive temperature ranges (Fig.1).



Source: Wikipedia

Figure1. Energy consumption pattern

Thermodynamic analysis of any process or system using various forms of energy brings clarity – viz. the cold and hot pinch points beyond which energy is necessary to be supplied from external source. The cold pinch point indicates the temperature and below which the cold energy is required and hot pinch indicates the temperature above which the heat energy is required to the process. The quantities of these energy levels are also defined through the pinch analysis. Poly generation facility will optimize the total energy needed which includes the electrical energy along with Heat and Cold energy. A comprehensive analysis on Pinch, Resource Optimization and Thermodynamic Reversibility provides a true solution to net energy demands of any process or energy demand clusters.

This analysis becomes highly attractive when we integrate the fossil energy resource with renewable energy resource in hybrid manner. Numerous examples can be given to bring about the elegance of direct energy generation or poly generation systems. Industrial cooling or commercial space air conditioning is one common example where electricity driven compression based system is compared with thermal driven absorption system. Fundamental analysis clearly shows the superiority of direct energy conversion (Absorption system) compared to electricity driven systems. Superimposed on this is the renewable energy source like solar, biomass or geothermal, the advantage becomes obvious. But in reality, the electrical driven systems in spite of low efficiency (of primary energy conversion and then long distance transmission) score over direct energy conversion system due to the distorted advantage the electrical driven systems in terms of cost of electricity over long years of industrial development. The current policy instruments like feed-in-tariff or Generation Based Incentives (GBI) are heavily skewed towards electricity. Large scale proliferation of electricity driven systems and ease of these devices in terms of plug and play makes substitute development challenging.

Therefore it requires tremendous advocacy to make feed-in-tariff based system applicable to those devices which in their function save electricity and hence act as “Virtual Power” generating device and therefore must attract similar (or even lower scale benefits will make them competitive) benefits which will make deployment of such systems far and wide and in the end makes a long term better option due to better efficiency compared with electricity driven systems.

In the following paragraphs, some of these aspects are illustrated in a comprehensive manner and the importance of poly generation systems of producing heat (cold and hot), electricity and even some cases generation of potable water from saline water using low grade heat available after the useful heat is converted into power is highlighted. Live case studies have been cogently discussed and experience of these in India is shared. The model can be a reference model for global deployment backed up by different policy instruments different sovereign countries have already put in place.

2. Integration of internal process optimization with external resource

The analysis of energy consumption pattern in complex nature of process technologies consuming large quantities of energy and integration of such complex systems with external energy resource has been a very fascinating subject for the energy scientists. In the current energy starved global scenario, need for such a comprehensive analysis using modern tools has been all the more felt essential and has percolated to all energy consuming facilities from process industries to commercial complexes and even extending to the residential buildings.

The concepts of zero energy building, self sufficient commercial complexes and “pinch compliant” process plant designs are now becoming extremely important from addressing the energy-environment conflict and climate change. This is greatly facilitated by availability of improved energy conversion devices, heat pumping systems, temperature and pressure swing systems using adsorption systems. The development of low grade energy pumping technologies, improved version Sterling Engines and thermo electric devices has enabled to switch heat and power in a manner that we are able to drive the system to its most optimum stage of energy consumption.

The integration of conventional energy resource with renewable energy resource has necessitated the need for such an integrated energy analysis all the more critical. Every process, industry or commercial activities require energy in the form of cold energy, hot energy and electricity typically known as utilities. While in an industrial or process systems heat and cold energy is required for maintaining process parameters, the commercial systems the hot and cold energy is required to maintain comfort conditions depending upon the geographical locations. Electricity is needed to run the energy systems in the form of pumping and compression needs besides the lighting and kitchen requirements.

Energy consumption is very often calculated based on the electricity consumption per unit of the product produced or per capita person employed in the commercial space. Thus specific energy consumption is measured as kWhr/kg of the product or kWhr/capita. The other forms of energy consumption is often measured in the form of specific consumption of the primary energy resource *viz.* liters (nm^3) of oil or coal per kg of the product. This is mainly due to the convenience or robustness of measurement of electrical energy and primary energy resources. Thus, except in highly intensive process industries, the kWhr and kilograms are used as energy index and no mention of kilo calories is made. This is convenient and all the commercial evaluation of energy costs can be evaluated based on these two measurements.

However, analysis based on energy utilization as described in the following would help in better understanding leading to better integration of resources.

3. Resource optimization and integration - An example

At the scientific and technological level, analysis is required at three levels.

3.1 First level

There are multiple level energy consumption patterns in any complex systems be it a complex process industry, or a commercial complex or even a residential buildings. The quality and quantity and type of energy consumption vary and every energy conversion or energy usage device puts a penalty in terms of efficiency and quality of waste energy that it leaves behind. A careful study of such Energetics reveal that it is possible to study the pattern of energy consumption of any process or systems and then analyze from both the first and second law of thermodynamics and then evaluate at each energy level the possibility of use/ supply of energy from the level above or below respectively.

This is indeed a fascinating subject and would become an important tool for the energy scientists in their search of minimizing energy consumption levels without any compromise to performance of the system. Such an analysis will then be able to identify the different levels of net external energy import facilitating the use of poly generation concept as an extension of such an analysis.

A typical analysis will reveal that there are several possibilities of interconnecting the energy systems within any complex systems so that the net energy import can be minimized. The "pinch analysis" is a classic case of use of this concept in most scientific basis and bringing in the complex network of heat looping systems. The grand composition curves being developed using the process of matching the energy content – mc_p - Temperature of the streams will enable identification of the cold and hot pinch points in a complex flow sheet so that the cold energy and hot energy need to be supplied only below and above such pinch points.

A case in point is a process consisting of chemical reactor followed by distillation column. (Fig. 2)

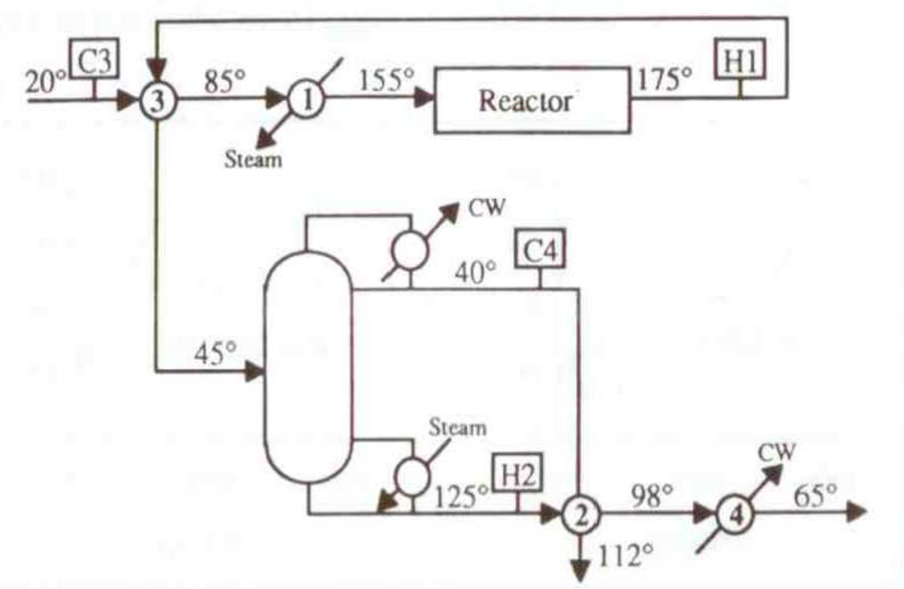


Figure 2. Original process without optimization

The first law analysis for the above process indicate that if the heating requirements is balanced against that of cooling requirements, then the net heat required is only 55 kW. Apparently this analysis does not consider the energy levels – and hence a second law analysis is necessary.

3.2 Second Level

The thermodynamic second law analysis show that there are different possibilities for interchange of heat and this requires considerable skills in identification of such internal net work of heat exchanges. The methodology is illustrated in advanced text books and not repeated here. The analysis of the process illustrated above show that after doing the "pinch analysis" and calculating grand composition curves, the hot utility of 605 kW is necessary at a temperature of above 145 °C and up to 185 °C, while the cold utility of 550 kW is necessary at a temperature below 22 °C and minimum at 7°C. The pumping / compression power is additional 300 kW. (Fig.3)

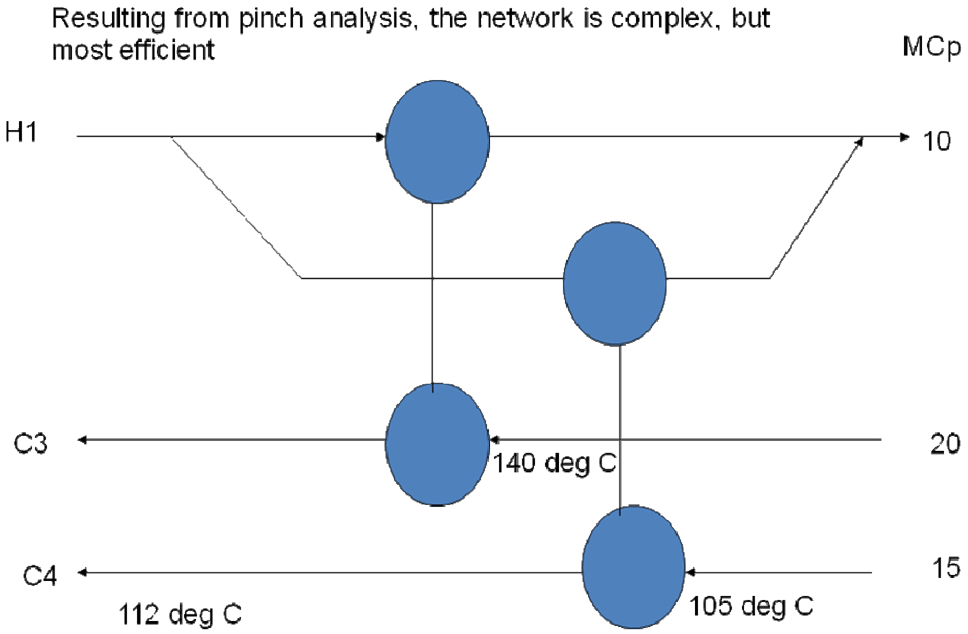


Figure 3. Optimized Network with 84% heat recovery

The technological demand during this stage of analysis is design of net work of heat exchangers using advanced heat transfer processes. The temperature approach assumed for the process determines the heat transfer area to be deployed and this is dictated by the type of heat exchanger design. The use of high efficiency heat transfer profiled surfaces and use of micro channels will enable enhanced heat transfer and hence allow for lower approach and better pinch temperature.

In the next stage, the concept of poly generation becomes very critical. One simple way is to generate the utilities independently and supply them to the process. A boiler of 605 kW generating steam at a pressure of 17 bar to meet the maximum temperature of 185 °C of the process, a vapor compression based cooling system to meet the chilled water requirements of 550 kW and import of net power of 300 kW plus power required to generate the above utilities will be one way of integrating the resource with the process. Clearly this will not be the best optimum process since though the energy needs of the process is optimized using the process of pinch analysis, the overall system will be hardly optimum due to obvious reasons.

This leads to resource level optimization exercise as to how do we then interlink various utilities so that the process and utilities are optimized simultaneously. In order to do this we need to have a deeper understanding on the various devices available to generate the utilities – hot, cold and power (HCP).

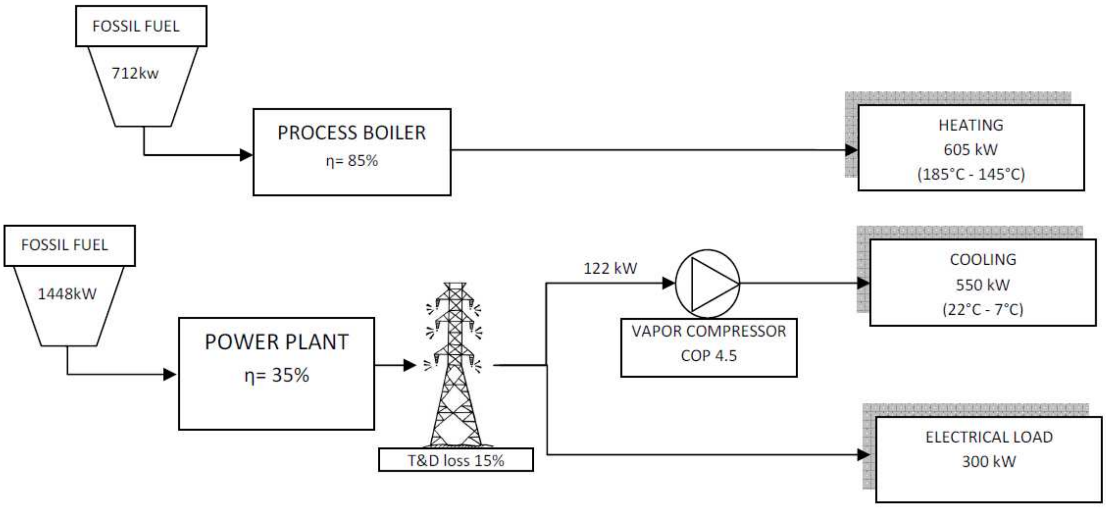
3.3 Integration of HOT utility and Power

This is fairly a standard integration concept of captive power plant in a combined mode cycle. Depending on the need of steam requirements in terms of pressure and temperature the design of extracting and back pressure steam turbine will be decided. In the above case the steam is required minimum 135 °C and maximum at 185 °C and hence we can have possibility of two extractions at the above temperatures or have one extraction and back pressure at 135 °C. The power and heat energy balance is extremely important to decide whether such a balance is possible. Assuming that the generating steam pressure and temperature is fixed at 480 °C at 60 bar pressure, under the back pressure condition, every kg of steam will generate 0.08 kW of power while delivering 0.65 kW of hot utility. Thus the ratio between hot utility and power is 8 which in the current case is clearly not a favorable ratio. (650 kW of hot utility and 300 kW of power). This would mean that we have to either import power net of what is generated from the combined cycle or have a condensing turbine to match the deficit in power.

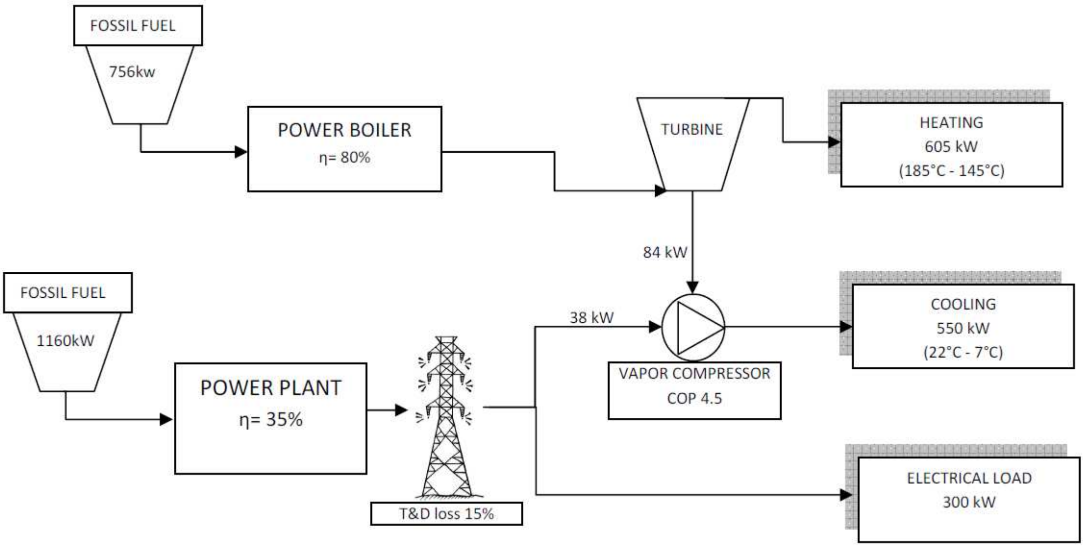
Taking forward the above discussions, we can integrate the heating with cooling energy requirements. 550 kW of cooling can be produced using steam extracted at 17 bar which can then be integrated with a triple effect LiBr system giving a COP of 1.8. This would further make the resource optimization more elegant. Various options available for meeting this requirement have been worked out and proposed in Table 1 and Figure 4. Options include use of renewable energy sources like solar energy. Capital cost and operating cost of the conventional scheme (option 1) are considered as base and capital cost factor and operating cost factor of 100 assigned to option 1. For all other options, relative costs have been worked out. Option 4 and 5 use solar energy and hence capital cost and operating cost comparison for these options with other is not very relevant. Operating costs include fuel and grid power costs. It can be seen that while both option 4 and option 5 use alternative source of energy in the form of Solar, only option 4 is eligible for operating cost benefits in the form of feed-in-tariffs.

Table 1: Evaluation of options considered

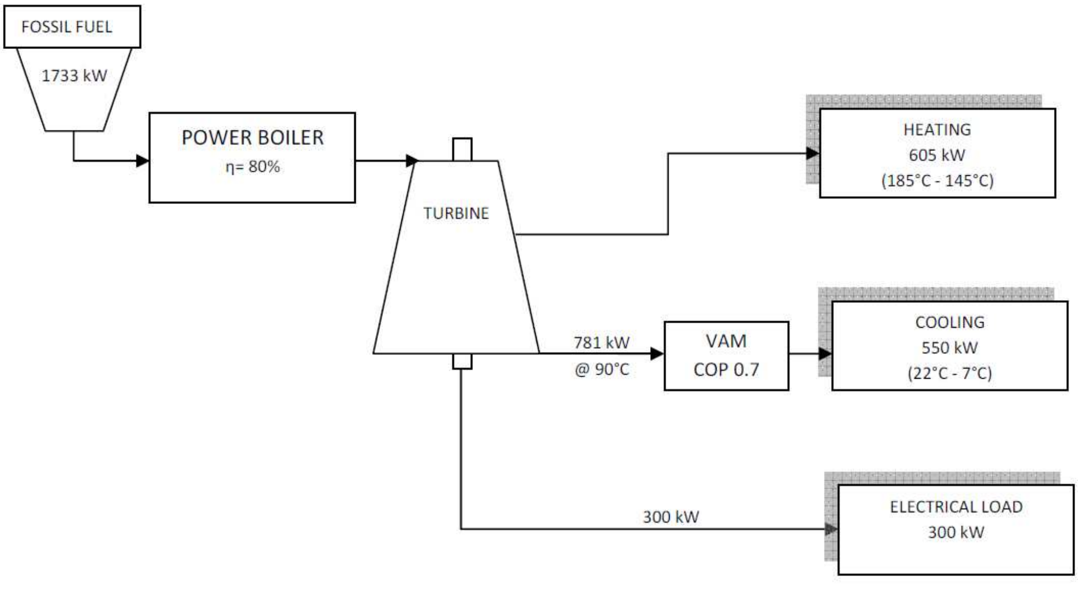
	Option 1	Option 2	Option 3	Option 4	Option 5
Capital Cost Factor	100	130	300	>>	>>
Operating Cost Factor	100	95	120	<<	<<
Fuel utilization Factor	100	88.8	80.3	35.0162	47.661
Total Fossil Fuel Input (kW)	2159	1917	1733	756	1029
Electrical power saving (kW)	-	-	-	338	0
Thermal power saving (kW)	-	-	-	0	998
Fossil Fuel saving (kW)	-	242	426	1448	1130
Collector area (m^2)	-	-	-	4000	2600
Feed-in Tariff (Rs/kW-hr)	-	-	-	15	0
Fossil fuel saved (kW/m^2)	-	-	-	0.36	0.43
Solar Operating cost benefit (Rs / hr)	-	-	-	5070	0



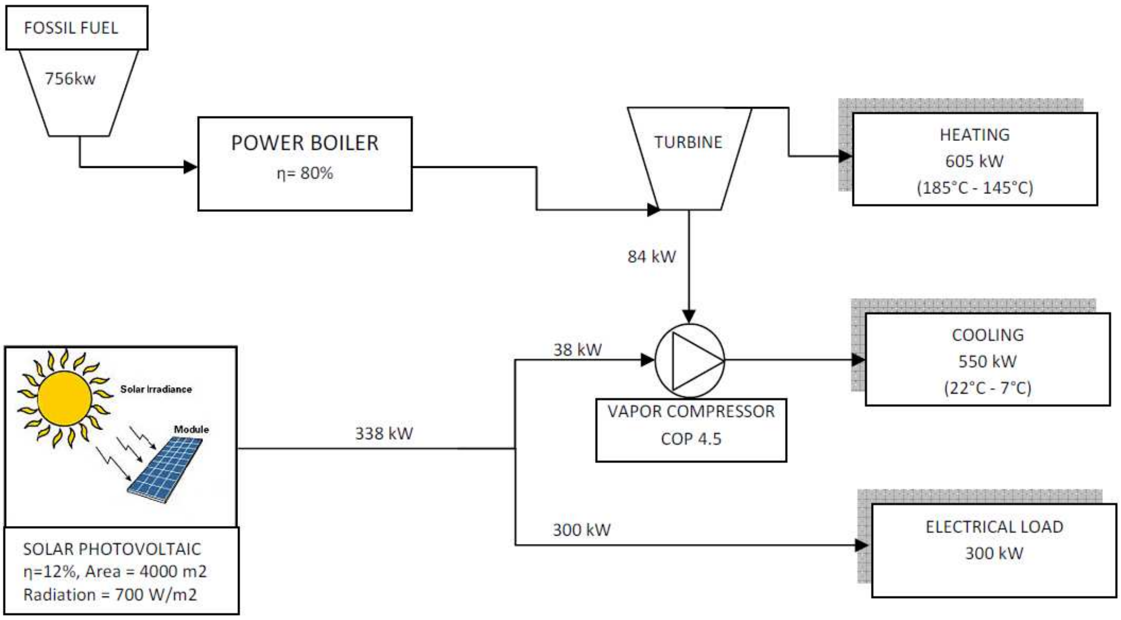
(a) Conventional Scheme



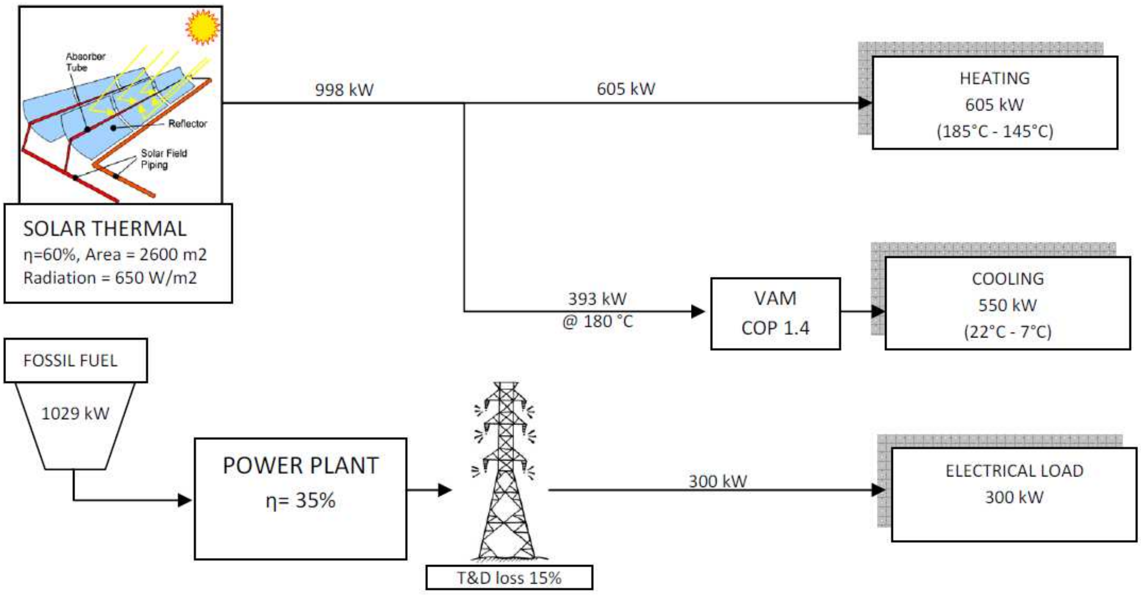
(b) Cogeneration with Heating



(c) Polygeneration with heating and cooling



(d) Polygeneration with solar PV



(e) Polygeneration with solar thermal "Virtual power"

Figure 4. Options for Polygeneration

The poly generation options shown in Figure 4 require integration of several technologies and systems. High efficient absorption systems using multiple effect concept or low grade adsorption based system, integration of solar thermal energy with fossil energy based systems are few such integration of multiple technologies for driving the utilities and process to the minimum energy consuming levels. The technologies mentioned above are not discussed in this paper but can be referred to in different journals and text books. The concepts like hybrid Sterling engine, thermo electric device as a topping cycle will also enable poly generation systems as a panacea for meeting multiple energy demands

4. Virtual power in cooling through Thermal route

As we move to highly integrated systems where electricity and thermal energy gets increasingly intertwined, it would require different measurement system or integrating the kWhrs with kilocalories. This is necessary especially when we are moving into renewable energy domain where the need is for a greater integration with all forms of energy consumption so that maximum advantage is derived out of highly capital intensive renewable energy technologies. Also this will try to correct many of the skewed policy instruments which have got created and are focused only on electricity generation systems. A simplest example is cooling energy which in India alone consumes 29% of total electricity generated and, if one generates solar cooling through Vapor compression route using solar electricity (PV or CSP) s(h)e gets the benefit of feed-in-tariff or generation based incentives, but this powerful incentive is not available when one generates same cooling using thermal energy. This distortion in the policy instrument globally needs to be corrected using the concept of “Virtual Power” where the final energy use is measured and converted into a common quantity (Fig.5). To produce 3 kW of cooling requires 1 kW of Solar electrical utilizing approximately 10 kW of solar energy assuming a 10% efficency at system level whereas to produce same cooling through thermal route, only 2.7 kW of solar energy is utilized.

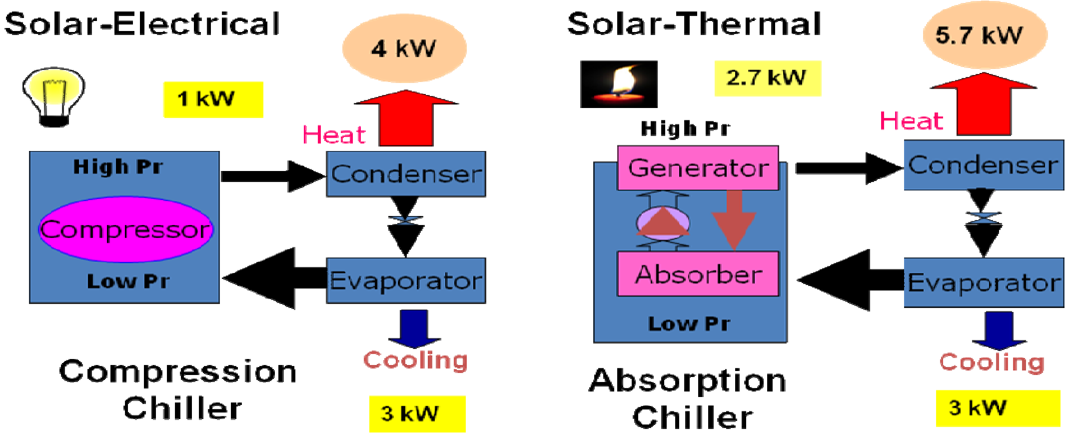


Figure 5. Solar Cooling saves electricity: generates “Virtual Power”

Similar is a case of process heating. In industrial energy utilization, almost 66% is consumed as “process heat”. While one third of this for temperatures below 200 °C where solar energy can be easily deployed. (Fig.6)

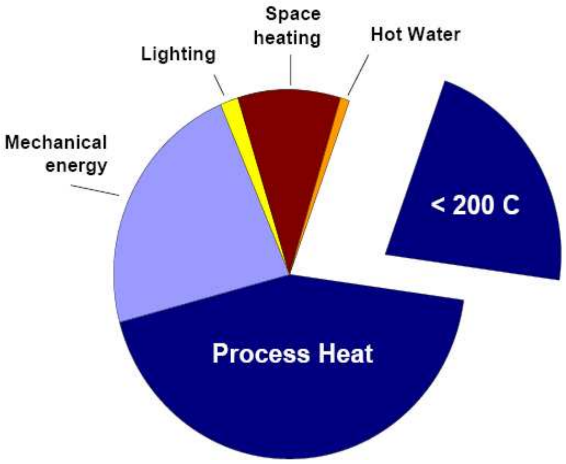


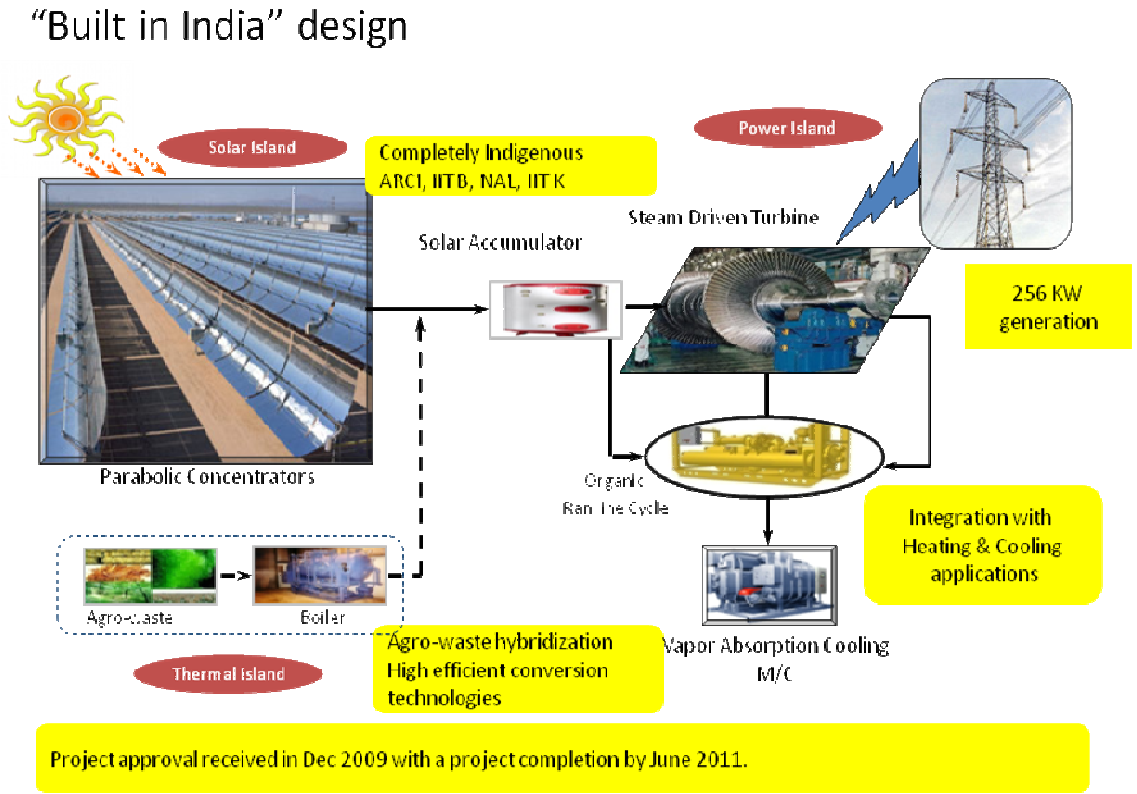
Figure 6: Industrial energy utilization

Current tendency in policy instruments is to provide capital based subsidies for Solar thermal technologies. Feed-in tariffs or possible tradable obligations made to electrical utilities to increase the share of renewable in their energy mix, prove more robust than plain subsidy schemes as the former ultimately make energy end users pay the bill and not tax payers. But solar thermal technologies do not deliver power but heat. While many countries have created incentive schemes for increasing the production of energy from renewable, most of these schemes do not provide any incentives for solar thermal technologies.

Challenges are measure of performance i.e. virtual power produced or tons of cooling generated.

5. Solar hybrid distributed generation power plant

There is yet another strong case for poly generation facility for a distributed generation power plant which is essential element in India's energy security option. This 250 kW demonstration project using solar thermal hybridized with bio mass and generating power and cold storage for agricultural produce in a rural setting (which otherwise use electricity driven vapor compression system) makes the entire system extremely attractive and viable option even in a rural setting. (Fig.7).



Project approval received in Dec 2009 with a project completion by June 2011.

Figure 7. Distributed generation demonstration plant

6. Proposed policy instruments

In order to make poly generation systems proliferate across the spectrum using renewable energy or more particularly solar requires more aggressive and sustainable policy instruments. The power saved in generating hot/cold utility needs to be quantified and provided with generation based incentives similar to the electricity generation incentives. As discussed in the previous paragraphs, typically in India electricity based cooling where the electricity is generated using solar energy gets a feed-in-tariff of nearly 25 $cents per kWhr of electricity produced. One unit of electricity generates approximately 3 kW of cooling (air cooled systems). The capital investment to generate 1 kWhr/hr electricity requires about 3000 $ of investment. The above 25 $cents per kWhr feed-in-tariff using a proper engineered system and financial model does give attractive returns on investment. This is a very good policy instrument to boost solar energy.

But such attractive policy instruments are not available when same cooling is carried out using solar thermal energy. A 3 kW of cooling requires approximately 2 kW solar thermal energy (at 1.5 COP), which in turn needs 5 m2 of solar collector area. Taking the cost of solar collector at 300 \$ / m^2 (the actual costs in India are much less) the investment needed for generating same solar cooling using this concept is approx 1500 \$ which is almost half of the first route. This means that even at less than half rate of feed-in-tariff would do exactly the same job as compared to electricity route.

The challenge of course is how to measure the cooling (or heating) energy and convert the same into equivalent to kWhr units which commonly represent the electrical energy.

Conclusions

The major conclusions coming out of the discussions in this paper can be summarized in following sentences.

1. Heat (and cold) is important form of energy use and is equally important to electricity. Every process using the multiple forms of energy needs to be optimized using modern pinch technology so that minimum heat and cold energy can be supplied from external resource.

2. At the resource level, further optimization is possible by using optimum allocation between heat, cold and electricity.

3. Several new concepts of energy conversion devices are available for making the system highly energy efficient. High COP absorption system, externally fired Sterling Engine, thermo electric generating systems, sorption and adsorption systems enable such integration.

4. When renewable energy becomes dominant portion of energy supply, the optimization analysis gets further complicated due to skewed policy instruments which heavily favour electricity generation.

5. To correct this, virtual power in poly generation system using renewable (solar) energy is a viable concept.

The development of poly generation systems which integrate multiple energy forms in a very innovative way and integration of renewable systems in hybrid manner with adequate policy instruments will result in unleashing the power of true “Energy Efficient Systems” which meets the principles of thermodynamics and reversible engine concepts.

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