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An Investigation into Solar Refrigeration Technology And Its Application To The Indian Agricultural Cold Chain

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Signed: Ashwin Philip Kurian Date: 26/09/2012

Abstract

India stands as one of the major food producers in the world. The green revolution and white revolution refer to the drastic increase in food grain and milk productivity respectively and changed India's position from being a net importer to becoming self-sufficient with regard to food production. Over half of its population is engaged in agriculture related activities. The agricultural produce market accounts for 14.5% of the GDP of the nation (Ministry of Finance, Government of India, 2011-12). While there has been a significant increase in the productivity from the 1950's, the wastage of food produce is extremely high. Estimates place post-harvest food wastage due to inadequate cold storage at 40% (Desai, October 2011) for fruits and vegetables alone without including dairy produce and food grains. This has a bearing on India's contribution to the world with regard to international food trade as although the country is self-sufficient, the export volume is comparatively low (Alam, 2006).The Ministry of Food Processing in India identified the cold chain to be a weak link in the food-processing sector. There exists much room for improvement in the cold storage and integrated cold chain infrastructure with regard to both capacity and operation. (MoFPI, Government of India, 2010). India is developing and while electrification is considered a top priority by the planning commission, there are still a great number of villages that are still to be electrified. Even the ones that are electrified have unreliable power (Gopal & Suryanarayana, 2011). This poses a challenge with regard to the energy required for refrigeration of food produce.

Hence, there exists a pressing need to develop a smaller capacity refrigeration system which can be operated independent of the electrical grid. This thesis is an investigation into the methods of refrigeration that can be adopted for the purpose of reducing food produce wastage. Specific focus on solar based refrigeration is placed due to the tropical position of the country that ensures adequate delivery of solar energy through the year.

Acknowledgements

I would like to express my gratitude to the many who guided my steps through the year.

To Dr Jae Min Kim, my patient supervisor who was always willing to guide with a smile, my sincere gratitude.

To my family and that one special girl, for their unrelenting love and support during my year at University, my love.

To my batch mates and friends, for this year of wonderful memories, thank you.

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1 Introduction: The Indian Food and Cold Chain Scenario

1.1 A brief summary

This thesis is an investigation into a solar driven solution for cold chain connectivity to support the agricultural base (specifically fruits and vegetables) in rural and remote parts of India where significant wastage of produce and consequent loss occurs due to the lack of refrigeration.

1.2 Structure of this document

The document consists first an analysis of the importance of Indian agriculture and its associated food industry growth trends in the years to come. Further to this, light is shed on the corresponding wastage that occurs across the perishable value chain.

In the following segment, the current state of the cold chain in India is analysed in view of the growing needs of the country and the barriers to its growth. This investigates the nature of the high value horticultural chain and analyses it in light of the available storage.

A review of refrigeration technology is undertaken following which the solar insolation of India is reviewed to expand further on the rationale for solar refrigeration made earlier on in the document. A focus on the solar refrigeration pathways through photo-voltaics and solar thermal leads into the analysis section of the document.

A literature review based deduction process is used to investigate the options for solar refrigeration and its confluence with the requirements of the agricultural (horticultural) produce industry in terms of both storage and transport of produce.

This is made to deduce the appropriate system for low cost solar based refrigeration for storage in and transport of produce from rural areas where electrical infrastructure is minimal thereby merging the social issue of food wastage with renewable energy systems and sustainable growth.

1.3 India and its Socio-Agricultural Scenario

The recent Indian union budget (2012-13, p.179)places the contribution of agriculture to the GDP of India at 14.5%.

The report draws attention to the 2001 census, according to which more than half of the 1.2 billion strong population at 58% is involved in agricultural activity.

India transformed from being a net importer of food since independence to becoming self-sufficient in its food produce through the green revolution for food grains and produce and through the white revolution for dairy products.

Ample sunshine, diverse agro-climatic conditions and rich soil types support the production of various food and commercial crops.

1.4 The Indian Food Industry

1.4.1 The demand forecast scenario

Based on data from the central statistics organization of India, an analysis of the food and agri-business industry in India by Business Monitor International and KPMG (2009) identified that the Indian food market consumption was registering growth at a phenomenal 5.32% compound annual growth rate (CAGR).

This would place the market in 2020 at twice the value of 2010 levels. This is shown in the trend graph below. The industry has however exceeded this growth rate as can be seen in figure 2.

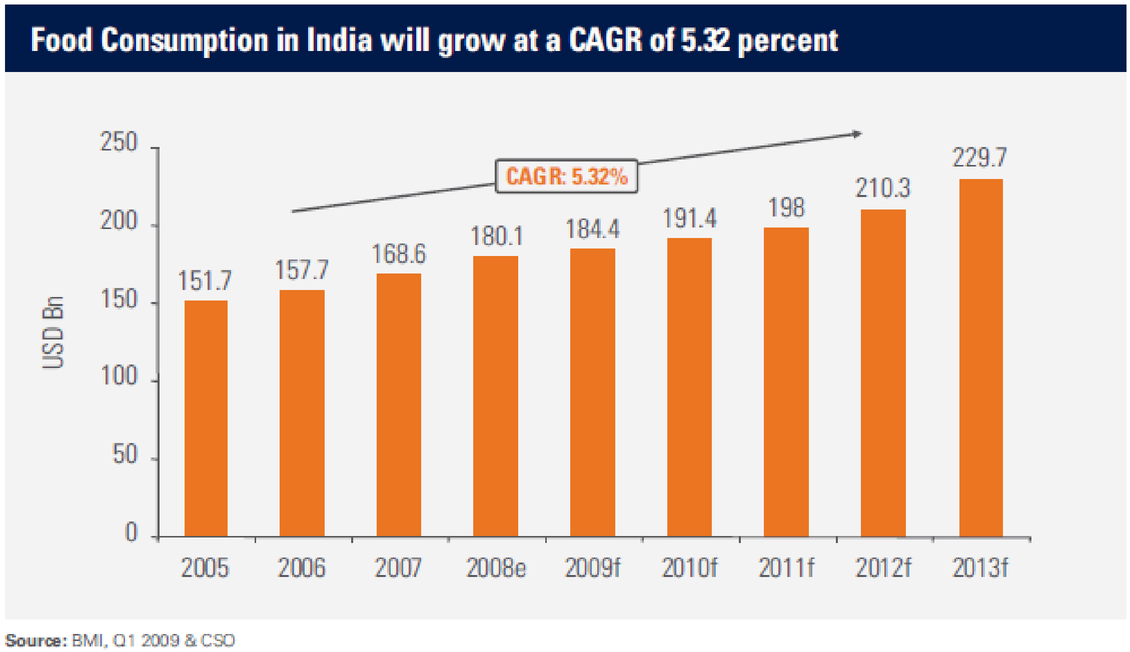

Figure 1: Food Consumption Trend in India, Source (KPMG IN INDIA, 2009, p.03)

A later analysis in 2010 confirmed that earlier projections had been exceeded indicating the firm growth in consumption (KPMG, 2011, p.1).

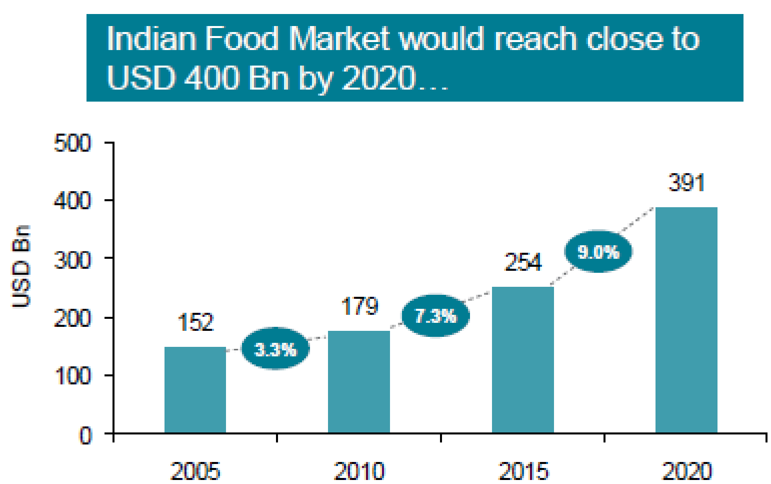

Figure 2: Food Market Projections to 2020, Source (KPMG, 2011, p.1)

1.4.2 Growth Forecast in Processed Food Industry and Organized Retail:

The food processing industry is expected to see growth at 7% CAGR driven primarily by urbanisation and sustained economic growth which opens the market to products at premiums

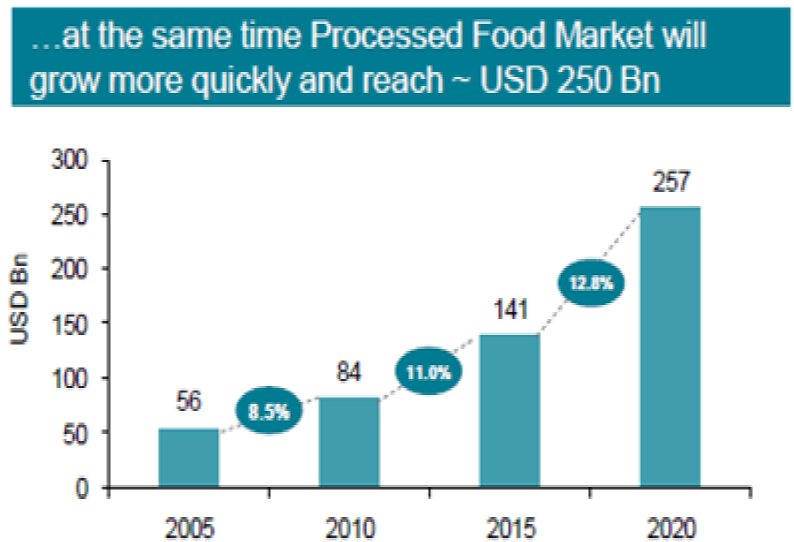

Figure 3: Processed Food Market Trends, Source (KPMG, 2011, p.1)

Based on analyses conducted by Technopak (2010, p.86), the food and grocery (F&G) market will continue to grow at close to 4.1% (real growth rate) till 2014. At present, the report estimates that nearly 98% of the F&G market is through unorganized retail through local stores.

"Based on estimates of value share of purchase of food in organised retail among the primary survey respondents (22% and 14% respectively for class A and class B cities) of over 1,160 consumers from across the country and based on the share of population of the surveyed regions in the total population, it is estimated that share of organised food retailing is about 1.44% of the size of food retailing, valued at Rs. 154 billion for 2008-09. Thus, the size of organised food retailing is very small compared to the size of food retailing. However, it is growing at nearly 150% as that of food retailing on the back of favourable drivers such as higher disposable income, growing proportion of youth in overall population, gradual increase in the share of population living in urban areas and increasing proportion of enrolment of women employees" (NABARD, 2011, p.2)[1]

[1] NABARD is the acronym for National Bank for Agriculture and Rural Development which is the apex development bank in India responsible for facilitating credit flow for agricultural and non-farm rural uplift and sustained development. (http://www.nabard.org/introduction.asp)

1.4.3 Growth Drivers of the food Industry:

A strategic plan by the Ministry of Food Processing Industries in India identified the following drivers for the growth trend in the food industry the excerpt of which is given below (MoFPI, 11th Plan of India, p.6).

Food and grocery dominates total retail spend: While rural consumers spend around 53%5 of their total consumption expenditure on food, urban India spends 40% of their retail spend on food items thus offering huge opportunity for processed food products.

Higher disposable income: High economic growth has led to increased disposable income for the Indian middle class, which is switching over to healthy and processed products. It is estimated that disposable income is set to rise at an average rate of 8.5 % by 2015. Also, the middle class is estimated to reach a size of 582 million from its current size of 50 million by 20156.

Shift in demographic profile: The median age of Indian population is 24 years and approximately 65% of Indian population is below 35 years of age. The large population of working age group forms a wider consumer base for processed products.

Increasing number of working women: The number of working women, as a percentage of the total female population, has grown from 12% in 1961 to close to over 25% resulting in demand for convenience food.

Emergence of organized food retail: It is estimated that the total food and grocery retail space will grow at a CAGR of 6% over 2006-2011, with the organized share likely to increase from less than 1% currently to 6-6.5%. This will translate into more business opportunity for processed products as well as provide forward linkage to the industry.

1.5 The Fruit and Vegetable [F&V] sector:

This thesis focuses on the applicability of solar refrigeration to highly perishable items with very low shelf lives.

Some reasons for this focus is because of the volume of the market that India can stand to cater and the trending towards horticultural cropping which is seen as producing better value for the cultivators. This notable shift towards horticultural crops is studied in a paper by Sharma & Jain (2011). Following is an excerpt of the same:

"The findings of the study reveal a structural shift in consumption pattern away from cereals to high value agricultural commodities, both in rural and urban areas, in the last two decades. This shift in dietary patterns across states and income classes is also observed. The results reveal a relatively strong and growing demand for livestock products and fruits and vegetables in both rural and urban areas. The average expenditure as well as share of beverages has increased by about six times in both rural and urban areas. Due to shift in demand pattern towards high-value crops, the farmers have also responded to market signals and gradually shifting production-mix to meet the growing demand for high-value commodities. This is reflected in the changing share of high value crops in total value of output from agriculture. The share of high-value commodities/products (fruits and vegetables, livestock products, fisheries) increased from 37.3 percent in Triennium Ending (TE) 1983-84 to 41.3 percent in TE 1993.94 and reached a level of 47.4 percent in TE 2007-08. The trade in high value products has also increased during the last decade. Overall, fresh fruits and vegetables exports represent a very small share of domestic production and agricultural exports but have increased significantly."

India currently accounts for 13% of vegetable and 12% of fruit global annual production. While this is the case, India's global market share for produce trade in this sector is very low. However, poor processing facilities and weak infrastructure for post-harvest processes, storage and transportation lead to wastage of nearly 30% of this produce resulting in a very low share of the global trade at only 1.38% despite the strength of its supply base (KPMG IN INDIA, 2009). It aims to increase the food share from this level to 3% by 2015 (MoFPI, 2007)[2].

Horticulture contributes to 28% of the agricultural gross domestic product of the nation with the sector seeing rapid growth (Economic Times Bureau, 2012). A more involved analysis of this is undertaken further on in the thesis where an investigation into the present cold chain scenario for fruits and vegetables is made.

[2] MoFPI – Ministry of Food Processing Industries, Government of India

1.6 The Issue of Wastage

Along with the constant push for a rise in production levels, there is associated produce wastage. Although Rahul Goswami in his paper (Goswami, n.d.) challenges the FAO figure of 40% agri-waste, it is unanimously agreed that there is much wanting in the cold chain infrastructure that services the country. Below is a schematic of the agricultural supply chain:

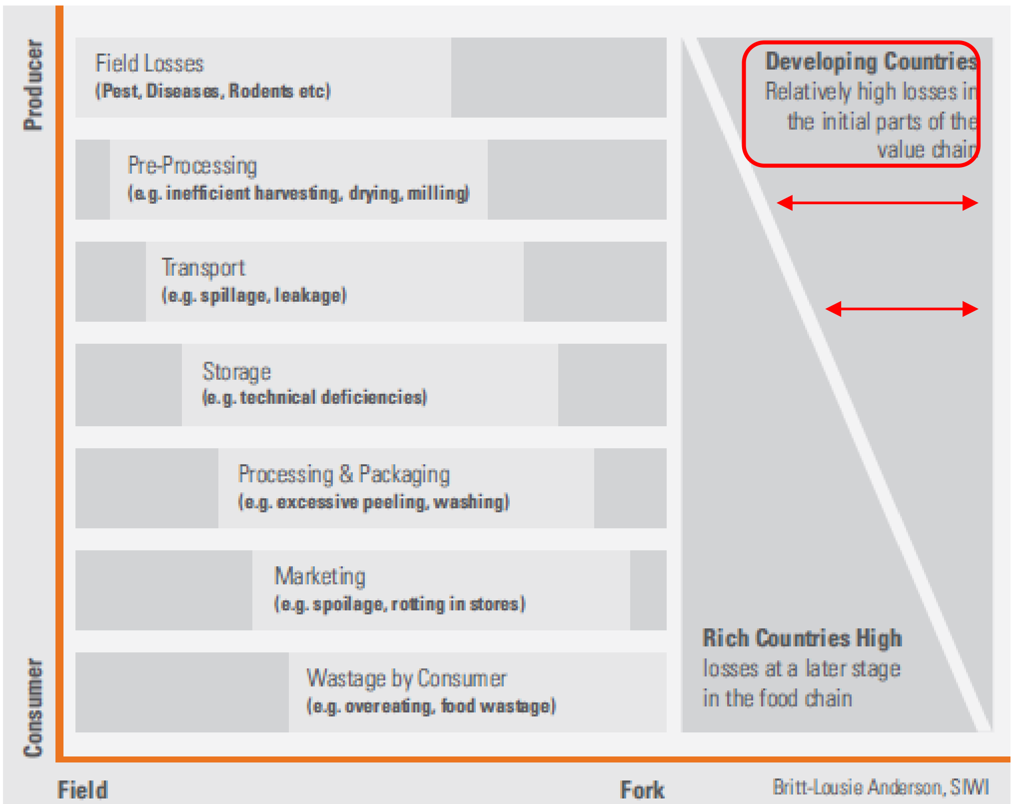

Figure 4: Developed and Developing Countries – Pattern of Food Losses, Source (KPMG IN INDIA, 2009, p.15)

To the right of the figure above, the two triangles are indicative of waste as it occurs in developed countries as opposed to developing countries. The lack of cold storage infrastructure, bad handling and less grading and sorting mechanisms results in tremendous wastage in developing countries as represented by the inverted triangle with more wastage occurring earlier on in the value chain at the farm level, pre-processing level and transport levels.

1.7 The Indian Cold Chain Scenario

A cold chain is supply chain which requires the control of temperature to protect the value of the perishable products within the chain.

This temperature control is required in many types of agricultural crops to enhance the shelf life of the produce and is required right from the moment the harvest occurs till it reaches the consumer.

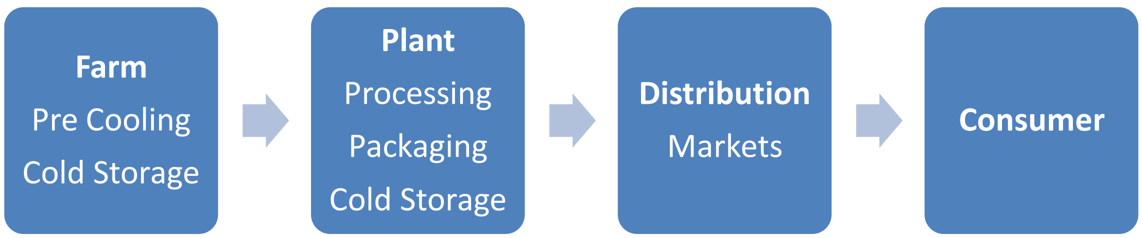

Figure 5: Cold Chain, Souce (Joshi et al., 2009, p.1261)

The impact of cold storage on the shelf life of some of the fruit and vegetable produce is indicated in Figure 6 below. The extra time would allow goods transfers across greater distances while maintaining quality and is thus indicative of the value that a strong cold chain can create.

Exhibit 11 **Impact of Cold Supply Chain on Shelf Life**

Commodity	Shelf life w'out storage	Shelf life with Cold Store
Apples	2-3 weeks	3 months
Mango	5-7 days	2 weeks
Grapes	4-6 days	3 -6 weeks
Litchi	7-8 days	3-4 weeks
Potato	4-6 weeks	3-8 months
Onion	15-30 days	5-6 months
Tomato	2-4 days	2 weeks

Source: Task-force report on Cold Chain by National Horticulture Board

Figure 6: Effect on Refrigeration on Produce Shelf Life, Source (Kapoor et al., 2012, p.5)

- **The Cold Storage Capacity of the Country**

The last documented official statistics from the government website placed the number of cold storage units within the country as 5381 with 4885 of them, over 90%, being privately owned (DMI, Ministry of Agriculture, Government of India, 2009) representing a total of only 21.7 million tonnes refrigeration with a deficiency of nearly 9-10 million tonnes (KPMG IN INDIA, 2009, p.59)[3].

This number has been increased as expected by analysts and a recent press release by the Minister of Agriculture, Sharad Pawar, informed the government that there are currently 7486 units at present (FnB News Bureau, 2011).

- **Capacity utilization of the existing warehouses**

Figure 7 below, the result of a Technopak analyses, indicates the capacity utilization of the cold stores within the country

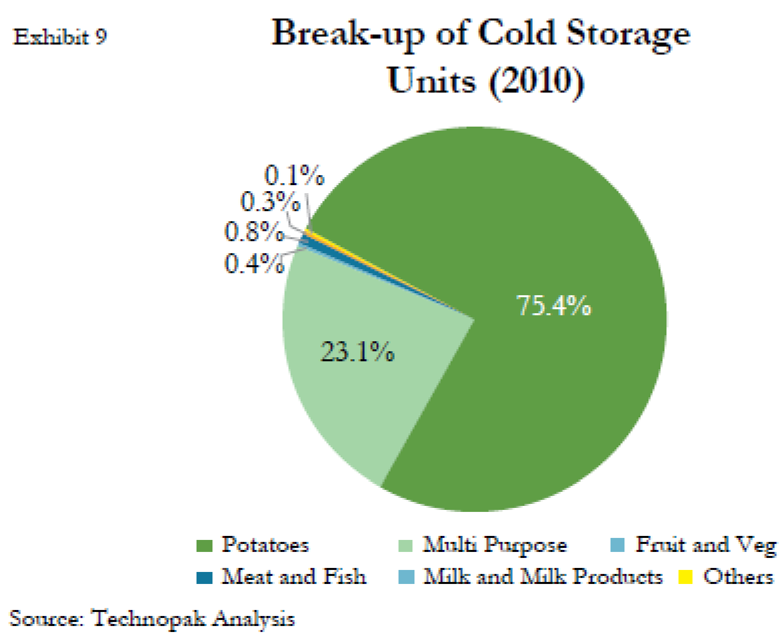

Figure 7: Commodity Wise Utilization of Cold Storage Capacity in India, Source (Kapoor et al., 2012, p.4)

[3] This report is a jointly undertaken by the ASSOCHAM - Associated Chamber of Commerce and Industry (apex chamber of commerce in India) and KPMG.

As per the figure above, over 75% of the cold stores cater majorly to one product, potato. Between the two harvest season, the Kharif and the rabi, this leads to extremely low capacity of utilization. A Business Today article (Adhikari, 2008) observes that the wastage in India is sufficient alone to feed countries like Vietnam and Brazil and re-ratifies government concerns about the gaps in the cold chain infrastructure within the country.

India, being one of the largest fruit and vegetable producers in the world having only less than 1% of its cold storage infrastructure inadequately dedicated to it begins to demonstrate the volume of the problem at hand. A paper by the director of the National Institute of Agricultural Marketing, M.S. Jairath (Jairath, post 2010), indicates that there is a stifling need for the promotion of enhanced shelf life for perishables. Cold storage capacity at present, according to the analysis conducted based on government statistics of cold storage infrastructure can serve only 12% of the total fruits and vegetables production. While 2 states have no facility for cold storage, other states like Jammu & Kashmir, Himachal Pradesh, Assam, Sikkim, Kerala and Tamil Nadu cold storage capacity to cater to less than 1% of the produce. Based on these figures, the paper draws attention to the fact that cold storage requires a boost in both the production as well as the consumption areas of the State.

- **Fragmented cold chain**

The indian cold chain is extremely fragmented with over 3500 players in this domain (Kapoor et al., 2012).

Further to this, any degree of fine control with regard to product redistribution and change in global capacity of utilization is a challenge as over 90% of the cold storage units are privately owned.

- **Uneven distribution of the present cold storage infrastructure**

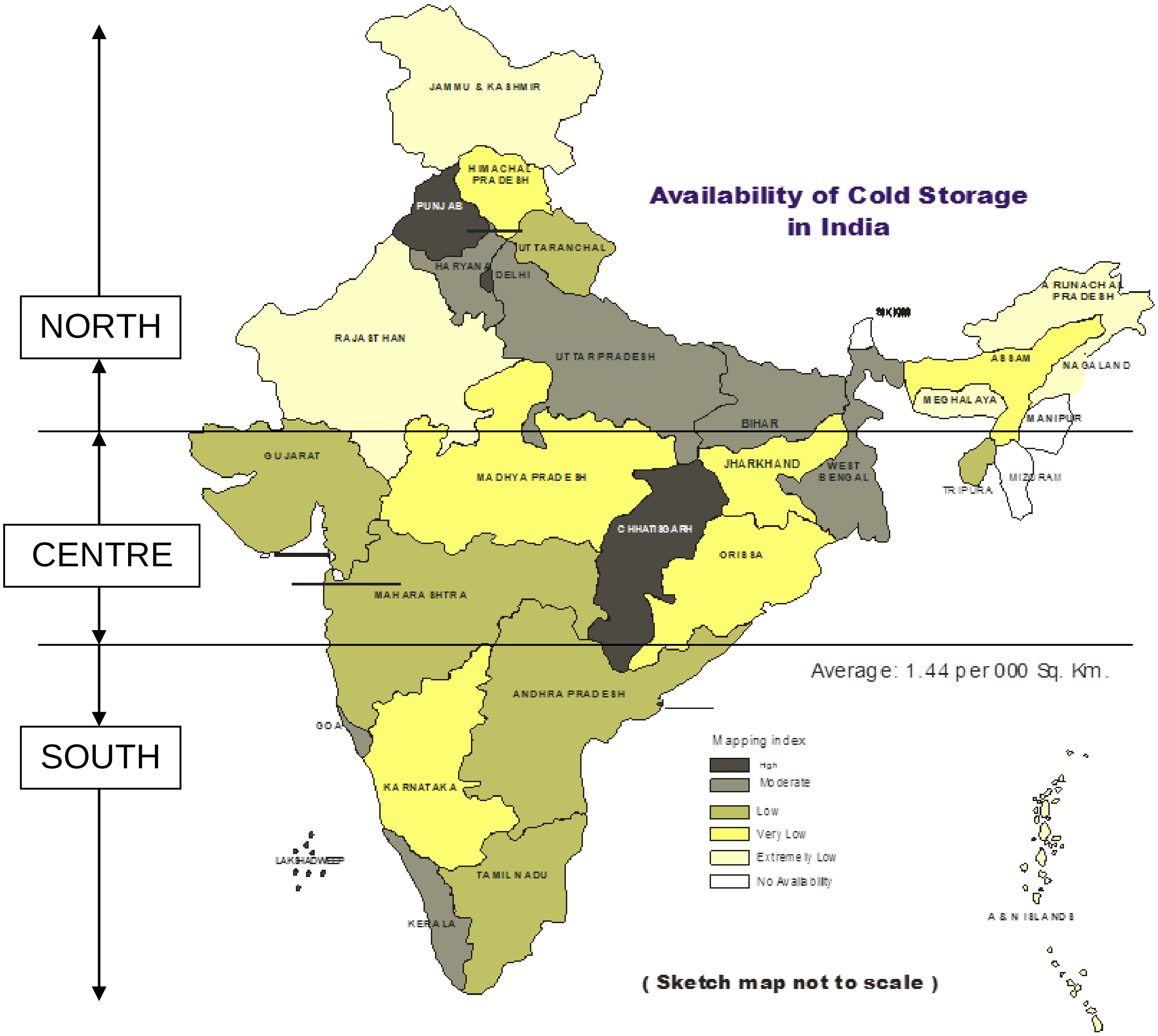

Figure 8: Cold Storage Distribution Density in India, Source (Jairath, n.d.)

The above figure, the outcome of an analysis by M.S. Jairath on the cold storage industry in India reveals the cold storage density and its uneven distribution within the country. As can be seen, several states of large area have either low or very low availability of cold storage units. Only about 2 states indicate a high with 5 others representing moderate cold storage distribution.

The following graph shows the state wise fruit and vegetable production.

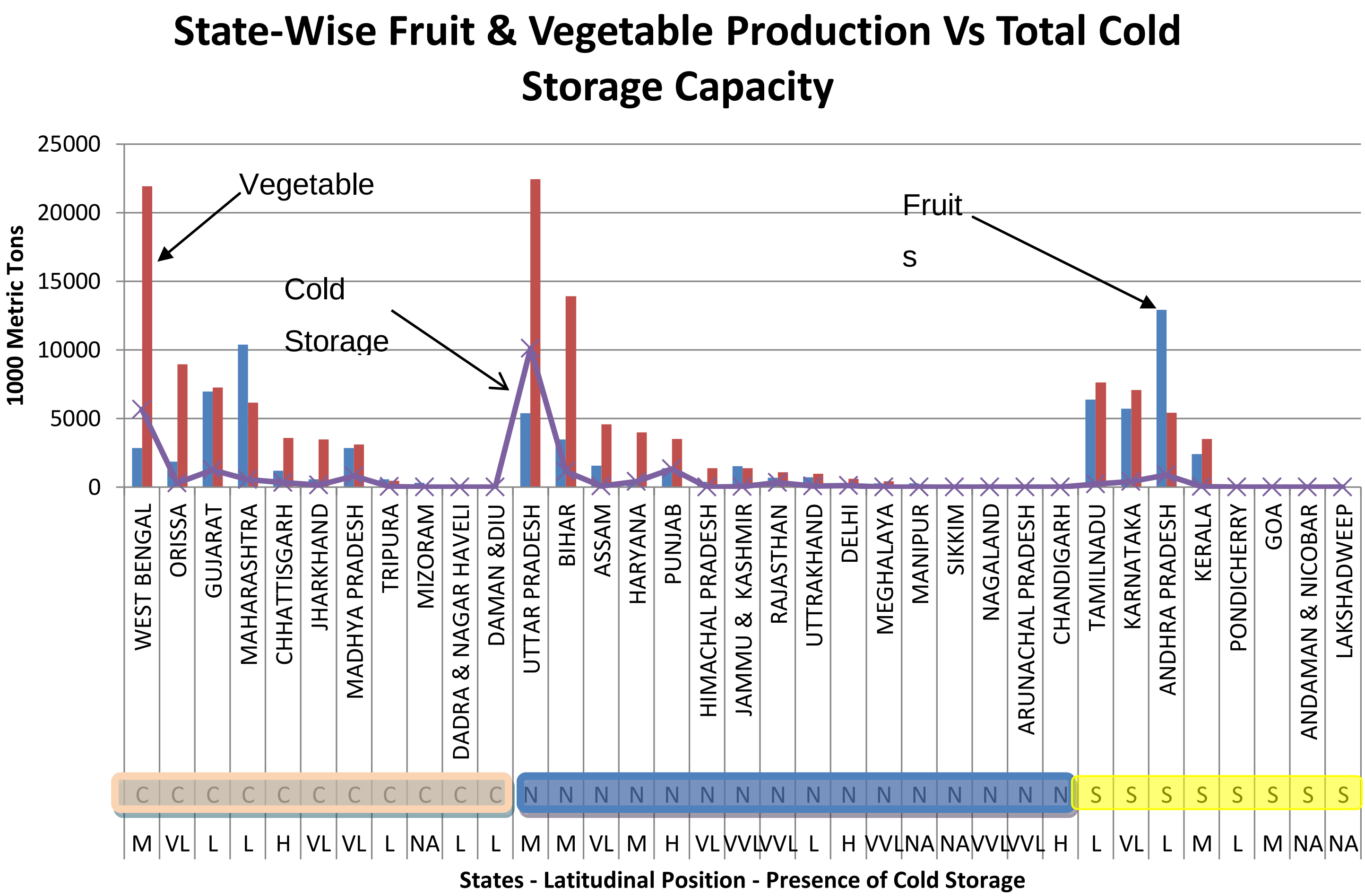

Figure 9: State-Wise Fruit & Vegetable Production Vs. Total Cold Storage Capacity

The graph was compiled using data from the National Horticultural Database (2011), and information regarding cold storage units published by the government via the Directorate of Marketing & Inspection (Ministry of Agriculture, Govenrment of India, 2009).

The graph segregates the nation into three latitudinal divisions, Central India – C, Northern India – N and Southern India – S.

The graph also combines the results of an analysis performed by the Director of the National Institute of Agricultural Marketing, M.S. Jairath which provided a statewise overview of the density of cold storage availability (Jairath).

Here the density of cold storage availability was given with the following notation with:

VVL – Very Very Low,

VL – Very Low,

L – Low,

M – Moderate,

H – High

The line graph is the series that represents the total cold storage capacity of the corresponding state. This is not indicative of the fruit and vegetable cold storage capacity. This is better represented in the figure below:

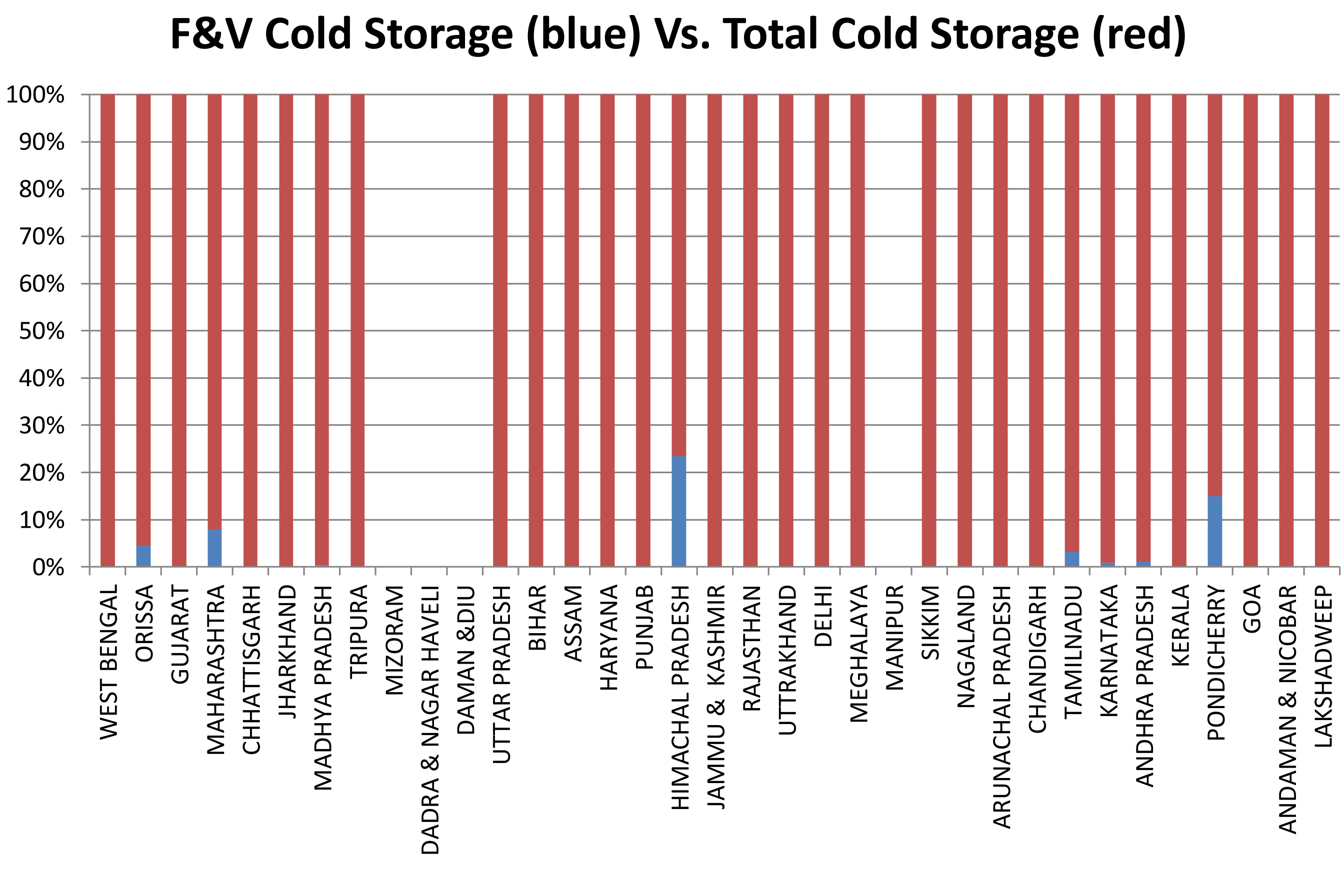

Figure 10: Fruit & Vegetable Cold Storage Vs. Total Cold Storage

This is indicative of the true deficit of fruit and vegetable cold storage for the market. As there are no refrigeration facilities at the market level, much of this produce is wasted.

This deduction is supported by several reports in the agricultural industry. In order to ascertain this, 2 states, Uttar Pradesh and Bihar in the central belt of India with a fair amount of sunshine and moderate density of cold storages were considered. A paper initiated by the planning commission examining the horticultural waste of Uttar Pradesh and Bihar (Association for Social and Economic Transformation) indicates that the lack of cold storage leads to a post-harvest losses of the order of 5% to 35%. These states are major horticultural producers in the northern latitudes of India and also have a moderate density of cold storage distribution have minimal provisions for the cold storage of fruits and vegetables. It further details that one of the major challenges encountered is the inadequacy of power which is a major hindrance to cold storage.

1.8 Challenges in Cold Chain Development

With the growth rate that is expected in the Indian food industry, the rate of growth in cold storage is insufficient to cater to the requirement. At present, as per the Government's working group of the planning commission in agriculture, only 10% of the fruits and vegetable produce in India have storage facilities (2011, p.11). The Federation of Indian Chambers of Commerce and Industry in a study of the bottlenecks in the Indian food processing industry (2010) reports that the government has policy drivers in place which includes capital subsidy schemes, reduction of import taxes and allowance of 100% foreign direct investment in the cold storage sector. The recent Indian budget has awarded infrastructure status to the cold storage industry as a result of which the loan interest rates and import duties will further be reduced.

However, the cold chain experiences several challenges with regard to the larger cold chain storage units:

- **Availability of suitable land**

Suitably sized parcels of land for large cold storage facilities, close to easily accessible infrastructure, poses a challenge. They will require a large capital outlay in terms of land capital alone as the access to infrastructure such as roads and electric lines steeply increases the real estate prices.

- **Lack of rural road and rail cold chain connectivity**

Access via roadways and railways in rural and remote parts of India is a significant challenge. A major issue is the lack of connectivity with regard to transportation that the country faces. "Only about 48% villages are covered with road" (KPMG IN INDIA, 2009, p.40). Connectivity with respect to road and rail network determines both the state of produce, wastage and the cost with which a food network can be set up.

- **Lack of electrification and unreliable power in many rural and remote areas**

Another major problem plaguing the country at present is the lack of electrification to provide refrigeration. The electrification programme is a priority in the nation. However, much of India still remains un-electrified. Even where power is available, it is unreliable and the need to strengthen the network was highlighted in the recent catastrophic failure of 2012 which resulted in power loss across 22 of the 29 states in India. Erratic power supply requires investment in expensive backup generators which increases the capital outlay. The erratic power also results in significant operating costs due to use of fossil fuels such as diesel. The deregulation of the fossil fuel market has further served to raise the cost to cold chain units. With 30% (NewsDesk, 2012) of the cost of cold chains typically being attributed to energy cost, this cost component significantly affects the profitability. In a study of the growth drivers and challenges for organised retail in India Gopal et al. (2010) produced tabulated data from Enterprise Surveys indicating that even with places having existing electrical connectivity, the shortages are significant.

Power Outages

	Stores facing outages (%)	Outage incidents per month	Hours of outage per month	Losses from outages (% from sales)
All stores	82.9	26.9	65.1	4.6
Leading states	77.4	23	47.6	4
Lagging states	90.6	42.8	126.3	7.1
Ahmadabad (city with best	22.5	1.2	1.5	0.4
Gurgaon (city with worst power	100	91.6	339	17.2

Source: Enterprise Surveys

Figure 11: Power Outages and Cold Storage Losses, Source (Gopal & Suryanarayana, 2010, p.27)

- **Fragmentation of supply chain**

With the highly fragmented cold chain industry of over 3500 individual players, a systemic management of such produce from farmer to consumer is a significant challenge (Kapoor et al., 2012, p.4).

1.9 A summary of the situation

The inhibitors for cold chain development in India were studied by Joshi et. al (2009). It outlines that inadequate and unreliable infrastructure along with high cost for installation is a significant barrier. The weak infrastructure and the fragmented system of supply lead to a significant increase in the operational cost of the cold chain which are found to be double in India as compared to the west.

"Operating costs for Indian cold storage units are over $60 per cubic metre per year compared to less than $30 in the West. Energy expenses make up about 28% of the total expenses for Indian cold storages compared to 10% in the West. These factors make setting up cold storages difficult, unviable and uneconomical. About 30-35% of the losses can be reduced by transporting the freshly harvested fruits and vegetables in refrigerated containers thus closing this gap in the cold chain." (Maheshwar & Chanakwa, 2006)

1.10 Impact of inadequate cold chain infrastructure

- **Artificial scarcity**

The lack of storage creates an artificial scarcity as although there is overproduction, the bottlenecks in cold storage results in wastage of produce and true wealth.

- **Price point for farmers is marginal**

The lack of infrastructure forces the farmers to push the produce at a lower price to reduce risk of loss resulting in a lowering of prices to non-remunerative levels given the existing fragmentation in supply chains for produce. Farmer suicides are unsettlingly common incidents in India.

- **Loss of GDP**

India's export at present is only marginal despite the volume of production presently at 1.5% of the world share with a vision to enhance it to 3% (MoFPI, 2007). The figure below, an analysis by Anita et al. (2010, p.160) indicates that since the late 90's, agriculture has maintained a positive balance of trade. With regard to the existing net deficit, agriculture stands to contribute significantly to reducing the difference at a national level.

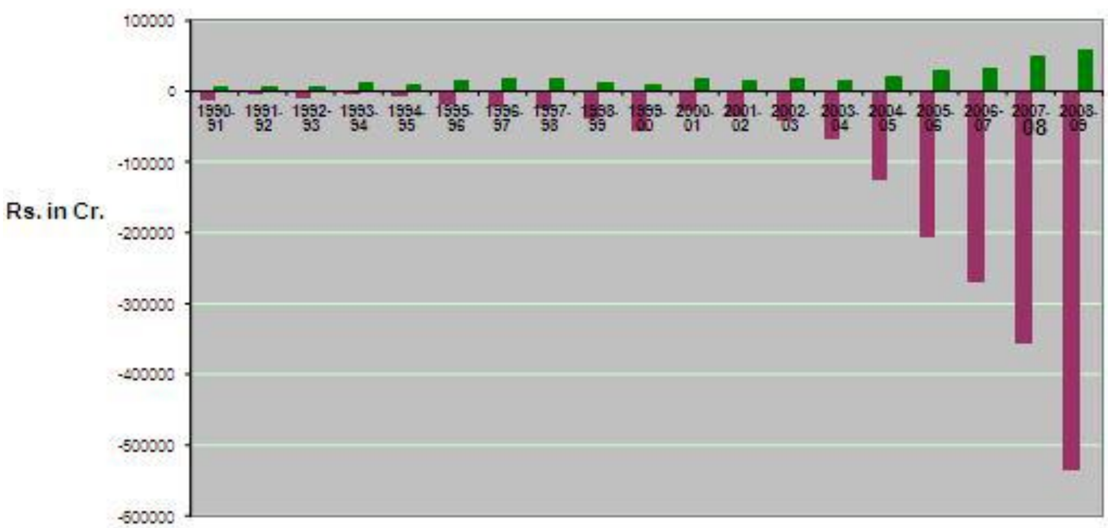

Figure 12: Balance of Trade - Indian Total Vs. Agriculture, Source (Patil & Kholkumbe, 2010)

1.11 The present need

The present need is to be able to provide continuous refrigeration through the agricultural supply chain starting right from the farm gate in a technologically viable, grid energy independent, economical manner with the ability to provide high capacity utilization rate.

The next section seeks to briefly explain the rationale behind the selection of solar driven refrigeration

1.12 The rationale behind solar powered refrigeration:

The challenge of lack in rural electrification and unreliable power led to the consideration of alternative energy technology routes for this purpose.

Amongst the possible technologies, the most abundant source which is also non-polluting is solar. This is analysed further on in the document based on studies conducted on solar insolation in India. In brief the rationale behind the selection of solar power to drive refrigeration is:

1. **Abundance of solar resource**

   India is situated in the sun belt between the latitudes of 40 degree south and 40 degree north with a suitable seasonal variation (from 4 to greater than 7.5 kW / m^2 / day) and annually averaging nearly 5.5 kW / m2 / day over nearly 60% of the landscape (Ramachandran et al., 2011). The variability in insolation with regard to the topography which would affect the direct radiation available in terms of the cloud cover formation is studied in a later section of this thesis.

2. **Lack of electrification at rural and remote areas**

   Although this is an issue that is a priority on the Indian Planning Commission, much of rural and remote India remains un-electrified. This opens the possibility to explore alternative energy solutions where the cost of the solution may be more profitable in view of the cost to electrical connection. The following graph is indicative of the extent of the rural electrification deficit.

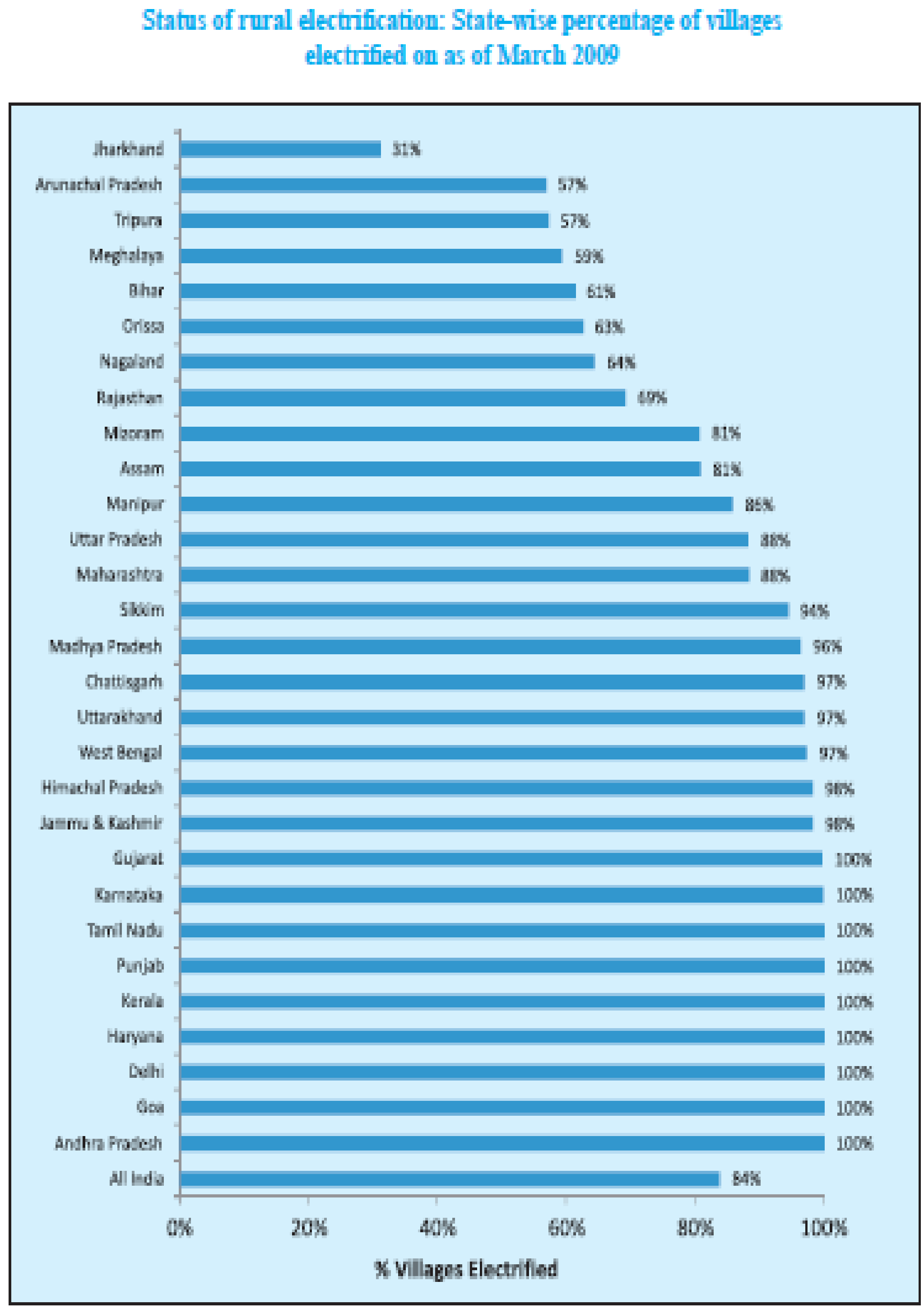

Figure 13: Village Electrification in India, Source (Power and Energy Division, Government of India, 2011, p.41)

3. **Current methods of electricity generation are fossil fuel driven and highly polluting**

   The following graph, an excerpt from the energy statistics report published (2012, p.16) by the central statistics office indicates the highly thermal fossil fuel driven energy base in India. This has a general efficiency of about 35% on average and leads to large volumes of green house gas emissions. While the per-capita energy usage is still low in the country, the report is indicative of the increasing trend in the consumption as well (p.47).

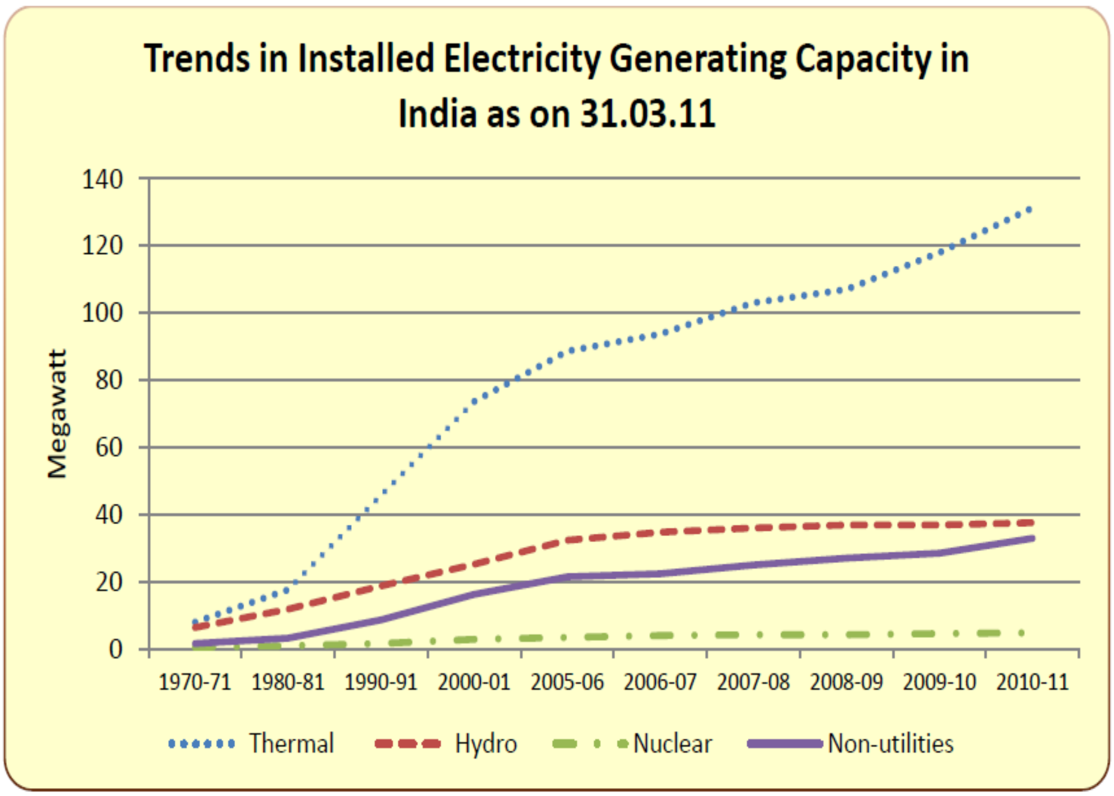

Figure 14: Trends in Installed Generating Capacity in India, Source (Central Statistics Office, Government of India, 2012, p.16)

4. **Inefficiency of existing power grid**

Even areas where electrical connectivity is present, there are significant power outages as described earlier. The transmission & distribution losses are significant currently estimated at 25% down from 34% in 2001 for all of India (Power and Energy Division, Government of India, 2011, p.36).

However, many areas in India have losses well above this average value. This can be reduced by producing energy where it is to be consumed as in the case of solar power.

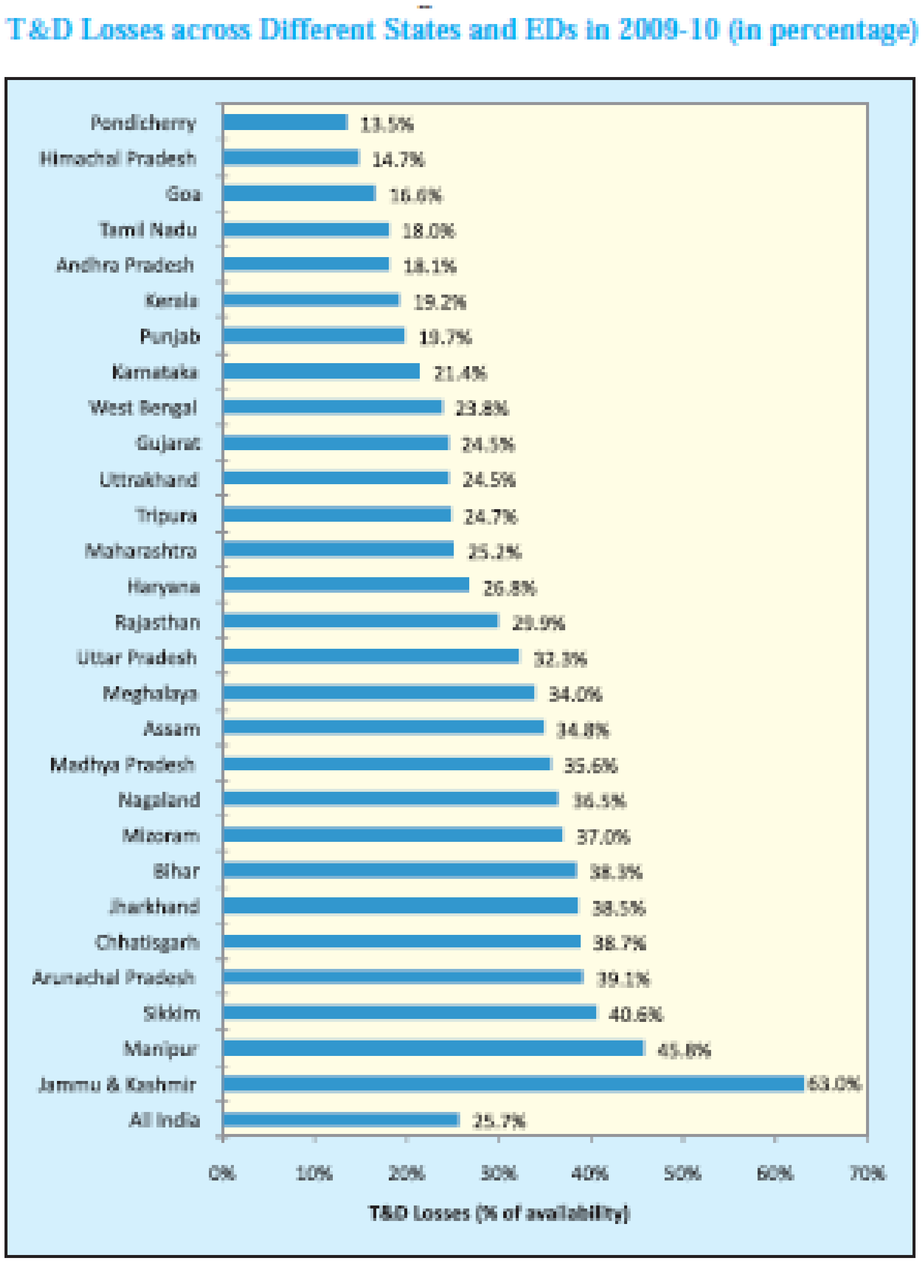

Figure 15: State-wise Transmission and Distribution Losses, Source (Power and Energy Division, Government of India, 2011)

2 Refrigeration Technology Overview

2.1 A Brief Introduction to Refrigeration

Refrigeration is the process by which heat energy is transferred from a lower temperature space to a higher temperature space. The fundamentals of the refrigeration phenomenon are governed by the second law of thermodynamics. This is expressed in two equivalent forms which are given below.

1. The Kelvin-Planck Statement: "No process is possible whose sole result is the absorption of heat from a reservoir and the conversion of this heat into work." (Spakovszky et al., n.d.)

2. The Clausius Statement: "No process is possible whose sole result is the transfer of heat from a cooler to a hotter body." (Spakovszky et al., n.d.)

In essence, it is impossible to transport heat from a lower temperature to a higher temperature without the input of some form of energy. This is shown in the figure below.

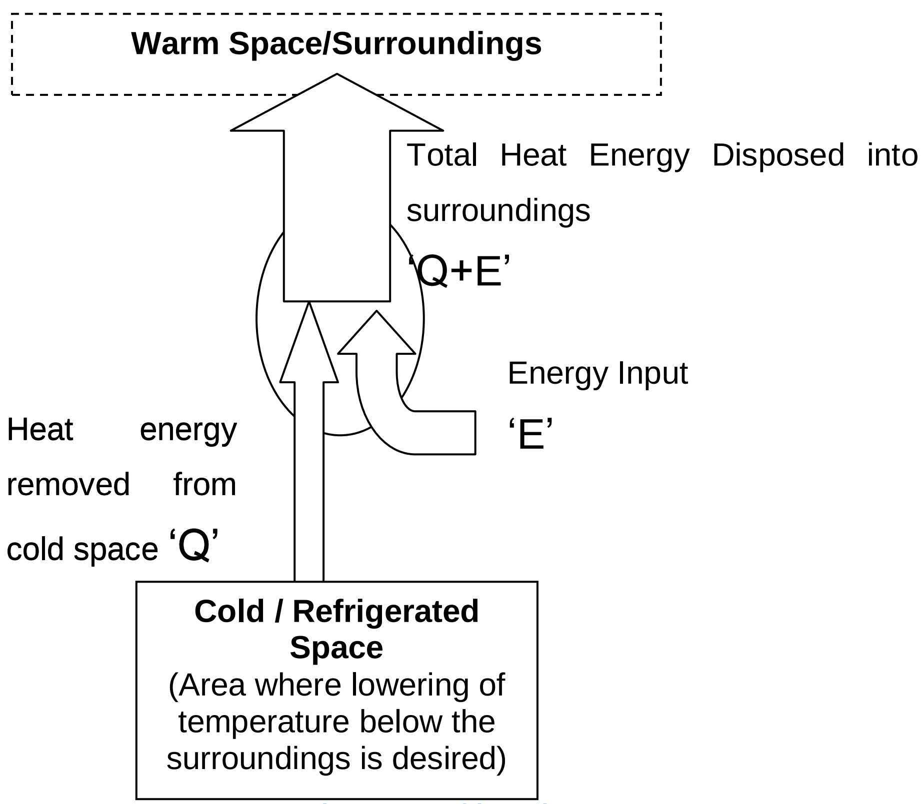

Figure 16: Refrigeration Process

In the figure above, the heat quantity ‘Q’ extracted from the cold space is supplied with an energy input ‘E’.

This is done so as to raise the temperature of the heat disposal end of the device to a temperature above the temperature of the surrounding. This allows for the heat to be discarded to the surroundings through natural heat dissipation from a higher temperature to a lower temperature.

2.1.1 Units of Refrigeration

The capacity of refrigeration system is measured in terms of power.

This is usually expressed in Wattage (kW), British Thermal Units per hour (Btu/h) or Tons of Refrigeration (TR)

$$1 \text{ TR} = 12000 \text{ Btu / hr} = 3.517 \text{ kW}$$

A ton of refrigeration refers to heat removal rate that will freeze a short ton of water (2000 lb or 907 kg) at 0 ° C (32 ° F) by removing the latent heat of fusion (333.55 KJ/kg or 144 btu/lb) in one day(24 hours).

2.1.2 Coefficient of Performance of a refrigeration system (CoP)

The coefficient of performance (CoP) of a system is defined as the ratio of the desired effect derived to the input provided. The efficiency of refrigeration cycles are compare on this basis.

For a refrigeration system, this is the ratio of heat removed to the energy supplied:

$$C.O.P._{ref} = (\text{Net Heat Removed / Net Energy Input}) = Q_{removed} / E_{input}$$

In order to investigate cyclic refrigeration, it is prudent to start at an ideal refrigeration cycle which operates on the reverse Carnot cycle.

2.1.3 Carnot Cycle (Heat Engines)

A system that runs on a thermodynamic cycle which has the capacity to convert heat to work is defined as a heat engine. It operates by drawing heat from a thermal reservoir at a higher temperature, performing useful work and discarding the residual thermal energy to a lower temperature thermal reservoir (Cengel & Boles, 2006, p.282). The efficiency of heat engines greatly depends on the individual processes from which the cycle is made.

The Carnot cycle was developed by Sadi Carnot in 1824 as an ideal theoretical thermodynamic cycle. This cycle cannot be operated practically due to irreversibilities that occur in the real world. A heat engine that operates on the Carnot cycle is known as the Carnot heat engine. It is of specific importance in the field of thermodynamics as it can be shown that it is the most efficient cycle to convert thermal energy to work.

In order to maximize the efficiency and therefore also the work output of a heat engine, the processes that make up the cycle need to consume the least amount of input energy or work and this is a natural consequence of reversible processes.

The Carnot cycle consists of four reversible processes; two isothermal and two adiabatic.

In order to understand the Carnot cycle, consider a cylinder-piston system filled with a gaseous working fluid operating between two ideal thermal reservoirs which have the capacity to keep their temperature constant regardless of the heat exchange to and from them. The four processes occurring in sequence occur as such:

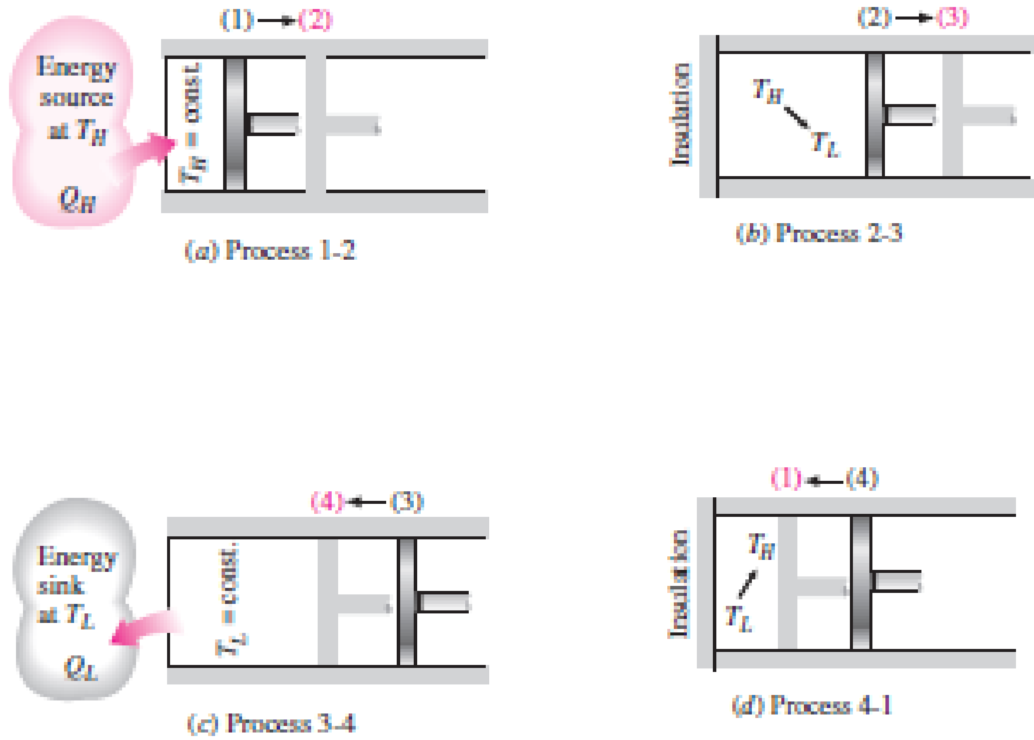

Figure 17: Thermodynamic Processes – Carnot Cycle, Source (Cengel & Boles, 2006, p.300)

1. Reversible Isothermal Expansion (Process 1-2): The engine absorbs heat 'Q_H' from a thermal reservoir at a higher temperature causing the pressure to rise driving the piston to expand out which results in both a lowering of the pressure and temperature. However, as the process is isothermal, heat will be drawn through the process to keep the temperature of the gas constant. Let the source absolute temperature be 'T_H'.

2. Reversible Adiabatic Expansion (Process 2-3): The engine is then placed in contact with insulation which forces the system into an adiabatic state and not allowing heat transfer to or from the engine. This forces the remaining expansion of the piston to occur, resulting in a drop of gas pressure and temperature.

3. Reversible Isothermal Compression (Process 3-4): The insulation is removed and the engine is placed in contact with a heat sink at a lower

temperature than the source. The piston then compresses the gas on the return stroke and as the heat is dissipated from the engine to the sink 'Q_L', the temperature of the gas is kept constant through the isothermal nature of the process. Let absolute temperature of the heat sink be 'T_L'.

4. Reversible Adiabatic Compression (Process 4-1): For the final process that returns the working fluid to the initial state in the cycle, the engine is placed again in contact with an insulated surface that results in the remaining compression causing a rise in temperature of working fluid to the initial.

   This can be represented on the pressure – volume plot as shown below where the processes are numbered correspondingly and the heat exchanges are shown. The area enclosed within the cycle is representative of the net work done during one cyclic process.

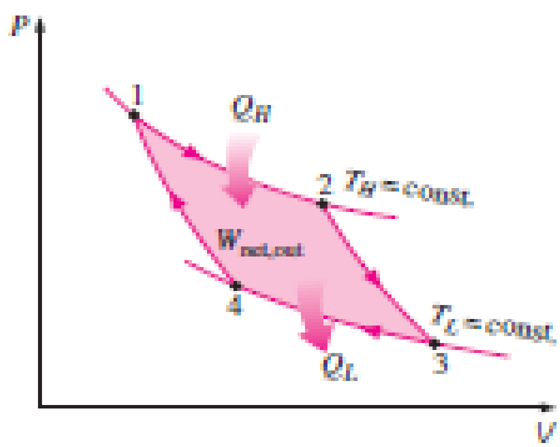

Figure 18: Carnot Cycle Pressure-Volume Plot, Source (Cengel & Boles, 2006, p.301)

The thermal efficiency of this cycle, which is the maximum possible efficiency, known as the Carnot efficiency is given by:

Thermal Efficiency = η_{th} = Net Work Done / Net Heat Input

$$\eta_{th} = (Q_H - Q_L) / Q_H$$

$$\eta_{th} = 1 - (Q_L / Q_H)$$

It can also be shown that this can be represented using solely the absolute temperatures of the source and the sink in Kelvin as follows:

$$\eta_{th} = 1 - (T_L / T_H)$$

2.1.4 Carnot Principles

This second law of thermodynamics establishes constraints that is expressed as the Carnot Principles which state:

“1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.” (Cengel & Boles, 2006, p.302)

2.1.5 Reversed Carnot Cycle (Refrigeration)

As the Carnot heat engine cycle is a completely reversible cycle, when the system is run in reverse, the cycle becomes the Carnot refrigeration cycle. In the reverse Carnot cycle, the heat and work interactions are reversed in direction and an input of work will therefore draw heat from the lower temperature thermal reservoir and discard the heat to a higher temperature thermal reservoir. This is depicted on the pressure - volume plot below:

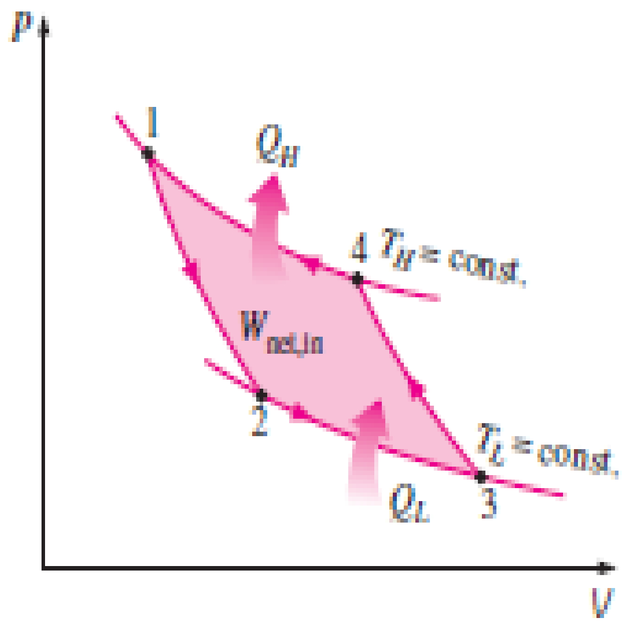

Figure 19: Carnot Cyle Pressure-Volume Plot, Source (Cengel & Boles, 2006, p.301)

Q_L amount of heat is taken from the lower temperature reservoir at temperature T_L, work is provided into the system and then Q_H amount of heat is discarded to the higher temperature reservoir at T_H.

Similar to the thermal efficiency of a heat engine being the maximum for a Carnot cycle, the performance of a refrigeration cycle is measured in terms of the coefficient of performance which is maximized for the reverse Carnot cycle.

$$COP_R = \frac{1}{Q_H/Q_L - 1}$$

Just as with the heat engine, it can be shown that the Carnot Coefficient of performance using thermodynamic principles can be expressed in only the absolute temperatures of the source and sink. This is expressed as given below:

$$COP_{R,rev} = \frac{1}{T_H/T_L - 1}$$

The corollaries of the Carnot Principles mentioned before apply for the case of refrigeration**.**

2.2 Refrigerants

The working fluid that is used to achieve the refrigeration effect by taking up heat is known as refrigerant. This heat absorption can occur through 3 distinct methods and may be classified accordingly as listed below:

- Refrigerants which absorb heat by changing phase and consequently absorb the latent heat of vaporization.

  These types of refrigerants normally are utilized in cycles where the heat extraction and heat disposal occur at different pressures.

  Normally, the refrigerant (at a lower temperature than the refrigerated space) changes from liquid to gaseous phase and absorbs heat in the latent heat of vaporization. This draws heat out from the space that needs to be refrigerated.

  The same refrigerant changes phase from gas to liquid by emitting the latent heat of condensation (same as vaporization) at a temperature higher than the surrounding environments. This allows the heat drawn as a result of refrigeration to be emitted to the surrounding environment which is at a higher temperature than the refrigerated space.

- Refrigerants in the second class absorb and emit ‘sensible heat’ and stay in a single phase during these heat transfer processes.

  This class is used in conjunction with class 1 refrigerants in order to achieve an intermediate lower temperature required by the refrigerated space.

- This final class of refrigerants are solutions of an absorbing media (known as the absorbent) and the refrigerated media which is absorbed such as a liquefiable vapour (absorbate)[4].

  The heat transfer is achieved through the heat of solution occurring as a result of the absorption (absorbate going into absorbent) and desorption (absorbate going out of absorbent) process.

Characteristics of a good refrigerant (Cengel & Boles, 2006, pp.616-18):

- High enthalpy of vaporization
- Good thermodynamic and transport properties
- Chemically stable
- Non-corrosive

- Non-Toxic
- Non-flammable
- Saturation pressure greater than one atmosphere is required to prevent air ingress into the system in the event of any discontinuity in the refrigeration system.
- Detectable in the event of a leak

- Environmentally Friendly
- Easily available
- Low cost

There are several refrigerants that are used in practice today. These include Chloro-Fluoro Carbons (CFC's), Hydrocarbons such as propane, ethane, ethylene etc., Carbon di-oxide, air and water as well.

[4] Solid media capable of 'adsorbing' vapours are termed as adsorbents and the 'adsorbed' media are called adsorbates.

2.3 Refrigeration Pathways

There are several methods to provide the refrigeration input energy 'E', mentioned above, required to create the refrigeration temperature differential.

The following diagram represents potential pathways to refrigeration:

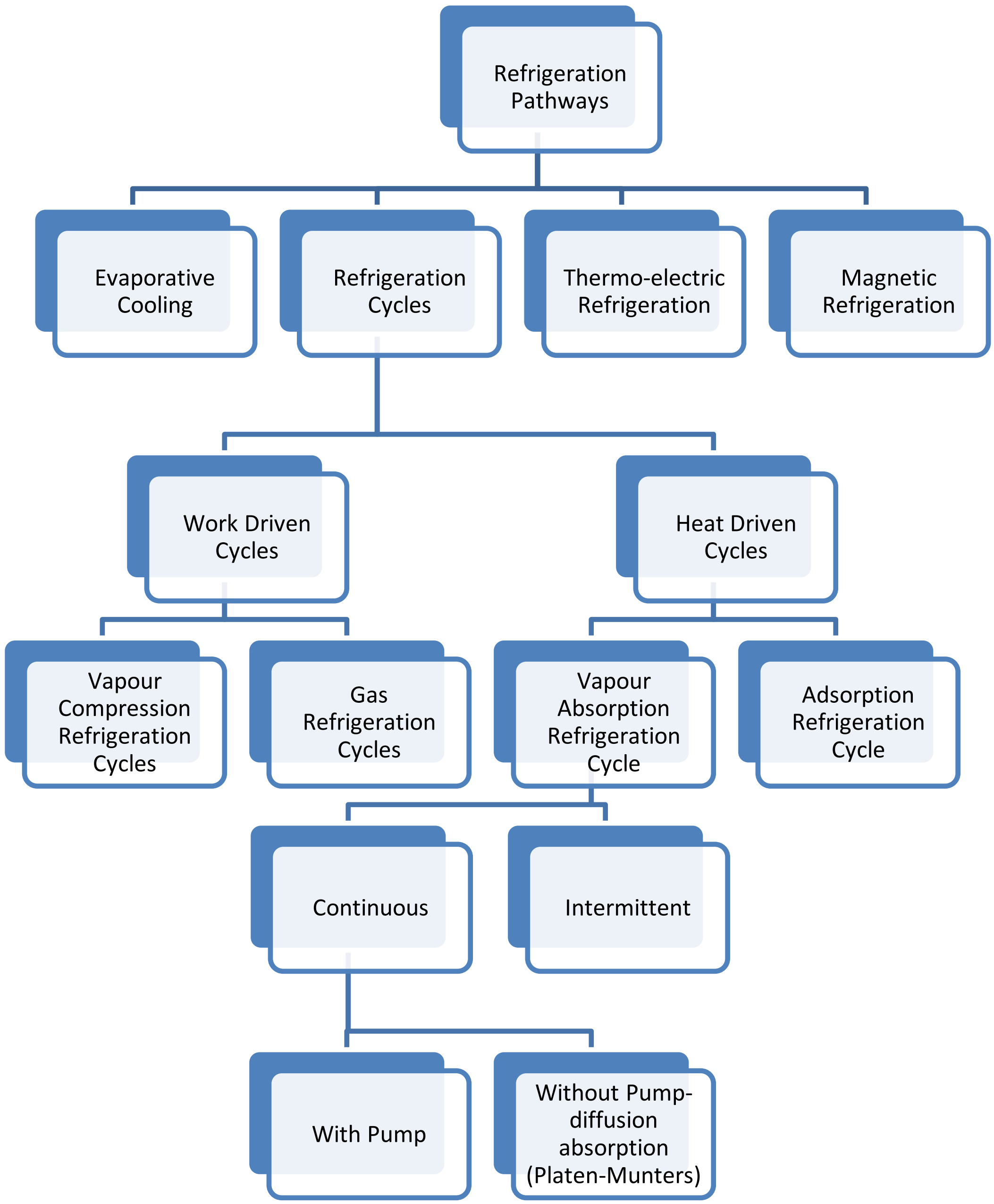

Figure 20: Refrigeration Pathways

2.4 Work Driven Cycles

2.4.1 Vapour Compression Refrigeration

The most frequently encountered system is perhaps the vapour compression refrigeration cycle and is used in home appliances such as domestic refrigerators. The physical set up consists of two heat exchangers, a compressor and an expansion device. One of the heat exchangers, placed with the cold space to extract heat is known as the evaporator. The second heat exchanger placed to interact with the warm space and discard heat is known as the condenser. A working fluid known as the refrigerant is circulated through this set up and it evaporates in the evaporator absorbing heat and condenses in the condenser by emitting heat; Hence the nomenclature for the two heat exchangers. A schematic of this is as shown below. Consider a refrigerator running a Carnot cycle below:

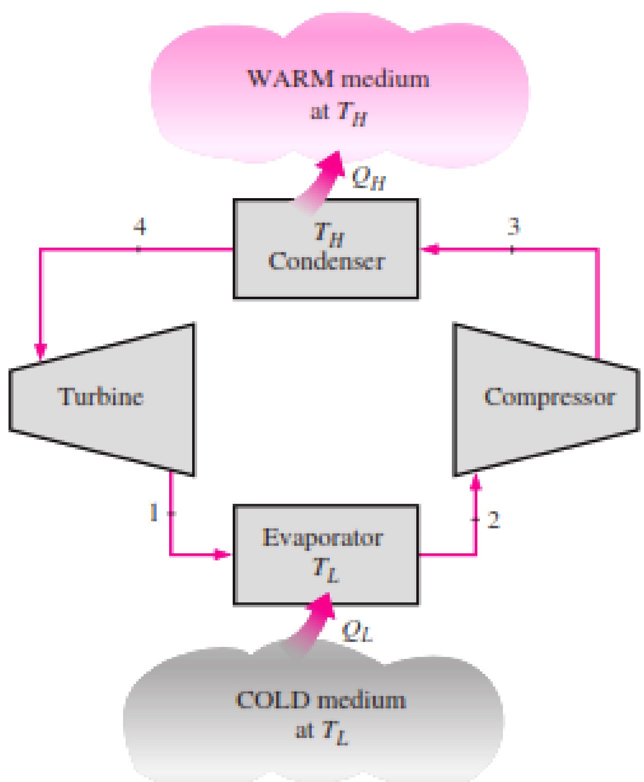

Figure 21: Vapour Compression Refrigeration Schematic, Source (Cengel & Boles, 2006, p.609)

The reversed Carnot cycle for the vapour compression refrigeration cycle is represented on the temperature - entropy plot under the vapour dome line as shown below:

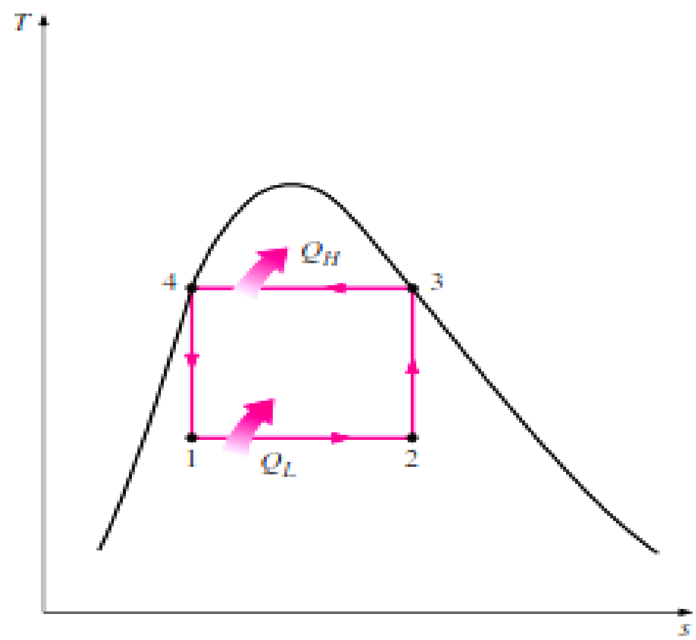

Figure 22: Vapor Compression Refrigeration Temperature-Entropy Plot, Source (Cengel & Boles, 2006, p.609)

The vapour compression Carnot cycle represented above, although the most efficient, is however impractical due to the following reasons.

1. The adiabatic compression process 2-3 will involve the compression of vapour to a precise state point which is difficult. Further, the vapour dual phase is hard to compress without severe damage to the compressor.

2. The adiabatic expansion process 4-1 will involve the expansion of vapour in a turbine from a liquid state which is practically complex due to the presence of liquid at during the expansion process which will again damage the turbine.

Modified Practical Vapour Compression Cycle Refrigeration

The reverse vapour compression Carnot cycle is consequently modified to practical process where the compression work is done outside the vapour dome. This is considered to be an isentropic expansion process for an ideal practical refrigeration cycle.

The expansion work is done by replacing the turbine with a throttling valve with some loss in process efficiency which is justified by the lower cost of the valve as compared to the turbine for the expansion process. This throttling processing is an isenthalpic process which is irreversible.

This modification from reversed vapour compression Carnot cycle to ideal practical refrigeration vapour compression cycle is shown in the figure below,

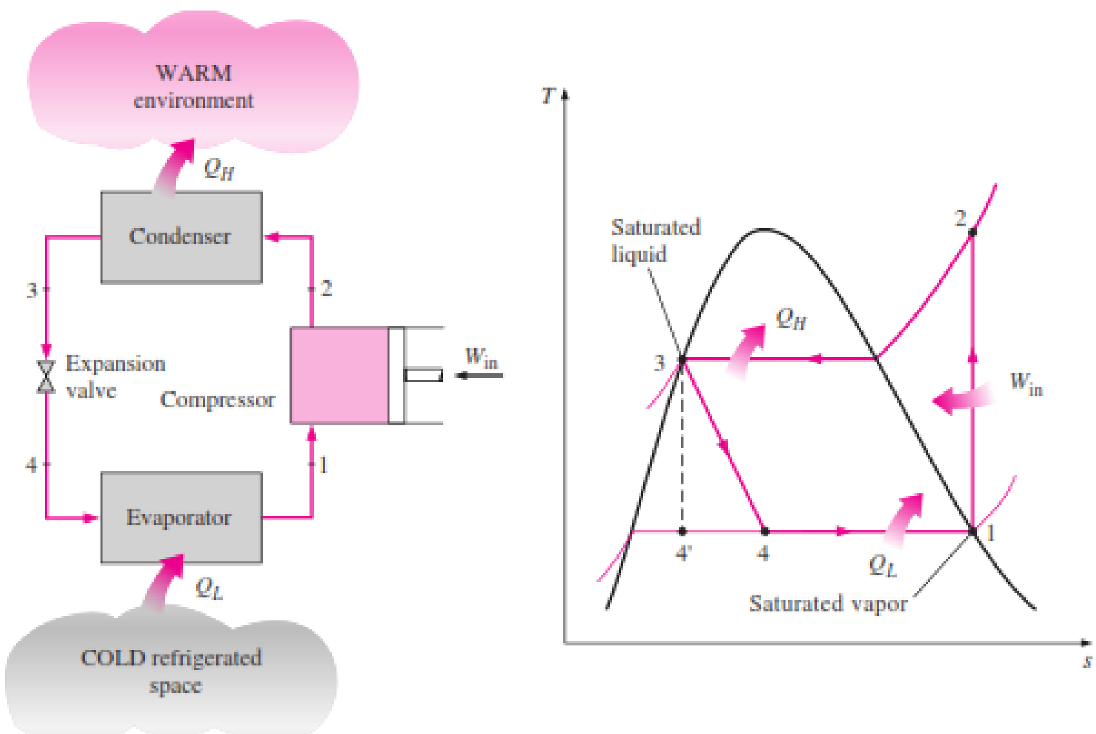

Figure 23: Practical Vapor Compression Refrigeration, Source (Cengel & Boles, 2006, p.611)

It is easiest to analyze this cycle on the pressure – enthalpy plot and the temperature – entropy plot depicted above is translated into the same and practical cycle is shown below

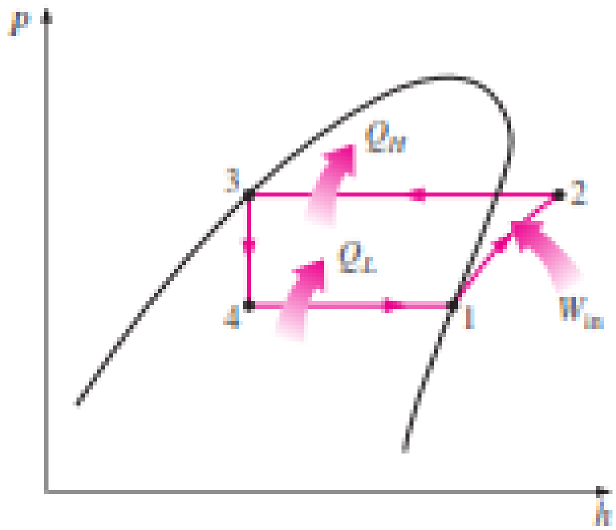

Figure 24: Pressure-Enthalpy Curve for Vapor Compression Refrigeration (Cengel & Boles, 2006, p.612)

The energy exchanges in the various processes are expressed through the enthalpy differentials. Let h_1, h_2, h_3, h_4 represent the enthalpies per unit mass of refrigerant at each state point 1, 2, 3 and 4. It is generally expressed as enthalpy energy / mass of refrigerant, usually expressed in KJ/kg. The processes here are as follows:

Process 1-2: Compressor - Isentropic Compression

$$W_{in} = W_{Compressor} = h_2 - h_1, \text{ KJ/kg}$$

Process 2-3: Condenser - Constant Pressure Heat Rejection

$$Q_H = Q_{Condensor} = h_2 - h_3, \text{ KJ/kg}$$

Process 3-4: Expander – Throttling

$$h_3 = h_4, \text{ KJ/kg}$$

Process 4-1: Evaporator – Constant Pressure Heat Absorption

$$Q_L = Q_{Evaporator} = h_1 - h_4, \text{ KJ/kg}$$

$COP_{refrigerator} = Q_L / W_{in} = (h_1 - h_4) / (h_2 - h_1)$

2.4.2 Gas Compression Refrigeration Cycle:

The gas compression cycle uses gas as the working fluid. Although they have lower COP, they tend to be light in weight as compared to vapour compression systems and since they are not limited by the vapour pressure where liquid vapour equilibrium exists, they can be used to bring down the temperature of the refrigerated space by a significant amount. The practical cycle is realized in the reverse-brayton cycle.

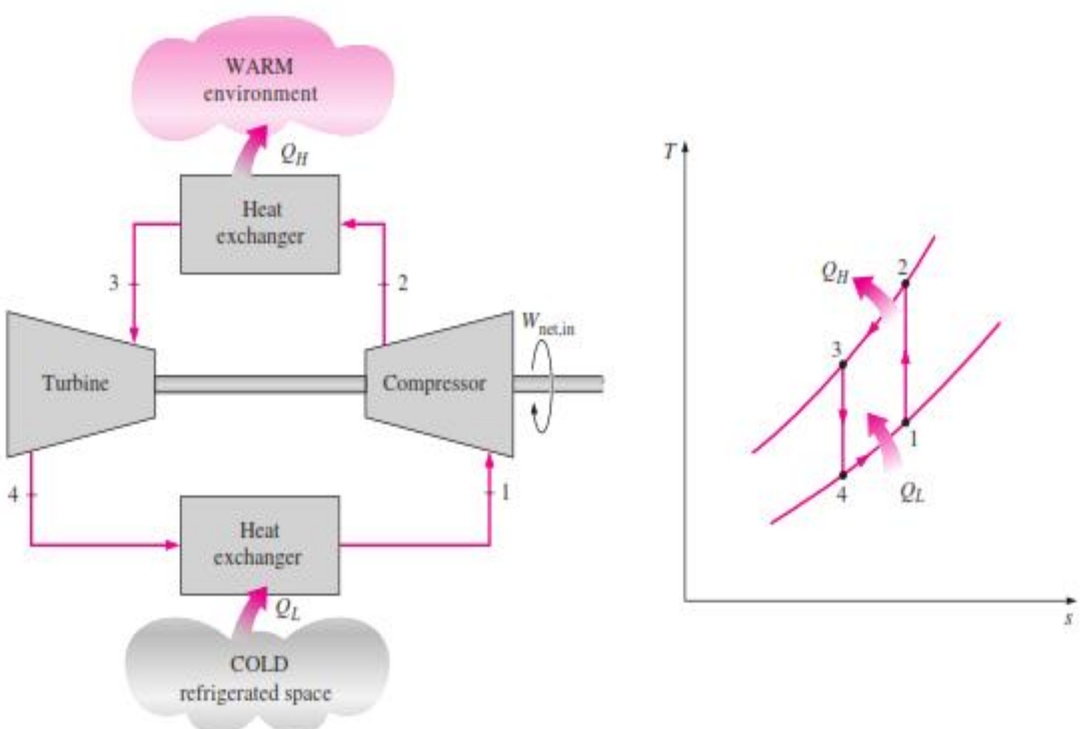

Figure 25: Gas Compression Refrigeration (Cengel & Boles, 2006, p.628)

The components of the cycle consist of two heat exchangers(interfacing with the refrigerated space and the external environment), a compressor and the turbine. Heat rejection and absorption occur at constant pressures. The corresponding state points are shown on the component diagram and the temperature-entropy plot.

Working:

Process 1-2: The gas enters the compressor where it is compressed consequently raising its pressure and temperature. Ideally this is an isentropic process. Work is provided into the cycle, W_{in}.

Process 2-3: This gas temperature exiting the compressor is higher than the surrounding and as a result of this, heat exchange (Q_H) occurs at constant pressure through the heat exchanger where heat flows from the gas into the surroundings.

.

Process 3-4: After the heat exchange, the gas is allowed to expand through the turbine in an isentropic process which reduces its temperature further through the reduction in pressure as a result of the expansion.

Process 4-1: During this process, the gas which is at a lower temperature absorbs heat (Q_L) from the refrigerated space at a constant pressure and then passes through to the compressor which draws in the gas at its inlet.

This cycle then restarts and the process repeats achieving the necessary refrigeration effect.

2.5 Heat Driven Cycles

2.5.1 Vapour Absorption Refrigeration

This vapour absorption cycle is almost similar component wise to the vapour compression cycle i.e. the condenser, evaporator and throttling device are kept as is.

The compressor however is replaced with an absorber, a generator and a liquid pump combination. With this system, the need for compression in the gaseous phase is eliminated, thereby significantly reducing the work input into the cycle. The pressure raising gaseous phase compression after the evaporator outlet is replaced with liquid phase pumping. These units together constitute what is sometimes conceptually referred to as a ‘thermal’ compressor.

Absorption is the process by which one substance in the gas or liquid phase enters another substance in the gas or liquid phase. The substance getting absorbed is known as absorbate and the bulk medium doing the absorbing is referred to as the absorbent.

The vapour that is formed in the evaporator by absorbing heat from the refrigerated space is pulled into the thermal compressor. This is achieved as the absorber unit contains a weaker constitution of absorbent which consequently has a lower vapour pressure while the evaporator is at a higher pressure due to higher refrigerant concentration. This pressure differential between the evaporator and the absorber due to differential in refrigerant concentration drives the vapour from the evaporator into the absorber to maintain equilibrium.

The refrigerant that is in vapour state is then taken into a solution through the process of absorption and is subsequently pumped to a higher pressure in the liquid phase. The absorption process is exothermic. The amount of refrigerant that is absorbed is inversely related to the temperature of the solution in the absorber and hence heat needs to be constantly removed from the absorber through a cooling water loop.

The rich solution that exits the absorber is then drawn into the liquid pump. This is then pumped into the generation chamber at a higher pressure. The heat source such as a burner provides the heat that separates the refrigerant from the solution. The refrigerant vapour that leaves the transport media in the generator is forced into the condenser, expansion valve and evaporator for circulation.

As opposed to the vapour compression cycle which is a work driven cycle due to the significant amount of compression work that is required to facilitate the cycle, the vapour absorption refrigeration cycle is a heat driven cycle and can utilize lower grade heat typically between a 100 °C and 200 °. Although there is pump work that is required as input, the proportion of pumping energy required as compared to the heat added in the generator is very nearly negligible.

The weakened solution leaving the generator is returned to the absorber under pressure which is reduced through throttling. A heat exchanger may normally be installed between the absorber and generator to minimize the heat input required at the generator by drawing on the heat of the weakened but heat solution returning to the absorber.

Within the condenser, the refrigerant vapour at a higher pressure and temperature discards heat to the environment which is at a lower temperature causing the refrigerant vapour to condense.

This is then allowed to pass through the throttling valve which decreases the pressure of the refrigerant and consequently its temperature. This allows for heat to flow from the refrigerated space to the refrigerant which absorbs the heat and in the latent heat of vapourization.

This cycle then repeats from the evaporator to achieve refrigeration.

The common refrigerant – absorbent combination used are

- ammonia – water
- water-lithium bromide
- water-lithium chloride

As water is used as a refrigerant in the latter two combinations, only temperatures that are slightly greater than the freezing point of water can be achieve.

The ammonia-water combination however has the capacity to reach extremely low temperatures.

Any heat source of suitable temperature can drive this cycle. The schematic of the cycle with the heat input provided by solar thermal energy is shown below.

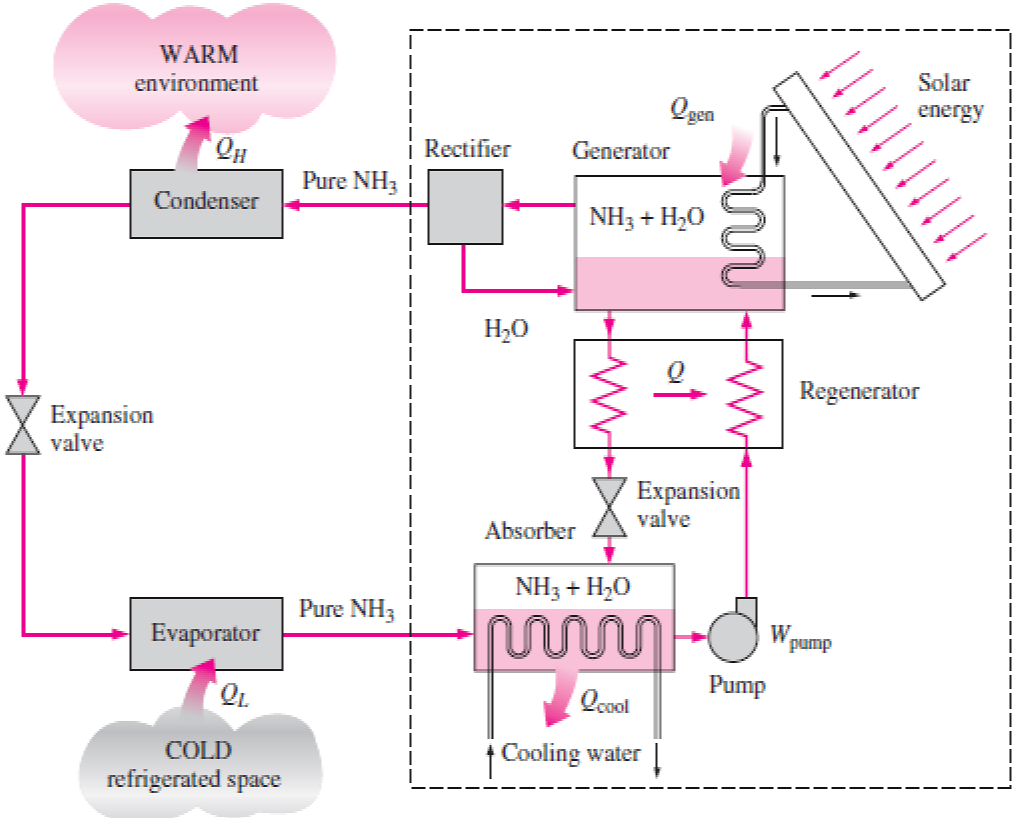

Figure 26: Vapor-Absorption Refrigeration Schematic driven by Solar Heat, Source (Cengel & Boles, 2006, p.632)

Coefficient of Performance

As stated before, the COP of a refrigeration cycle is given by

$$C.O.P._{ref} = (\text{Net Heat Removed} / \text{Net Energy Input}) = Q_{removed} / E_{input}$$

$$C.O.P._{ref} = Q_L / (Q_g + W_p)$$

Q_L – heat removed from cold space

Q_{gen} – heat input in the generator

W_p – work input to the liquid pump

As the work input is negligible ($W_p \approx 0$) compared to the heat input to the generator, the COP formulation can be reduced to:

$C.O.P._{ref} = Q_L / Q_g$

This can be expressed differently. The maximum heat that can be provided as an input to the refrigerator can be thought of as the useful energy output of a heat engine operating between the source temperature 'T_S' and the ambient temperature 'T_o'. The refrigerator operates between the temperature of the refrigerated space 'T_L' and the temperature of the surroundings.

As a carnot cycle has the maximum efficiency for any cycle operating between two temperatures, the carnot heat engine's work output is considered as the equivalent heat input to the refrigeration cycle.

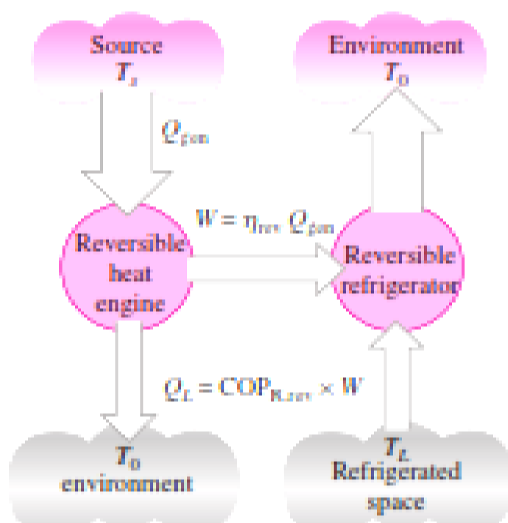

Figure 27: Theoretical Maximum Thermal Efficiency of Absorption Refrigeration Process, Source (Cengel & Boles, 2006, p.633)

The work output of this engine (equivalent to the heat input to the refrigerator) can be expressed in terms of the thermal efficiency and the heat drawn from the source as

$$W = \eta_{rev} \times Q_{gen} = (1-T_o/T_S) \times Q_{gen}$$

η_{rev} – Carnot efficiency of heat engine

The heat drawn from the sink is:

$$Q_L = COP_{R,Rev} \times W = T_L/ (T_o - T_L) \times W$$

$COP_{R,Rev}$ – Coefficient of performance of reversed carnot (refrigeration) cycle

It can be shown from the above therefore that the maximum COP for an absorption cycle is therefore (Cengel & Boles, 2006, p.633):

$$COP_{rev,absorption} = \frac{Q_L}{Q_{gen}} = \eta_{th,rev} COP_{R,rev} = \left(1 - \frac{T_0}{T_s}\right)\left(\frac{T_L}{T_0 - T_L}\right)$$

2.5.2 Diffusion Absorption Refrigeration Cycle (Platen-Munters Cycle) (Heat Driven Cycle)

The absorption refrigeration process is still limited by virtue of the requirement of a pump due the need to create a differential pressure between the evaporator and condenser sections of the refrigeration system. The diffusion absorption cycle also known as the Platen-Munters refrigeration process eliminated this need delivering a cycle which was purely dependent upon the absorption phenomenon and transfer of heat. The entire cycle operates at a single pressure. This was achieved by the use of a third fluid, an inert gas such as hydrogen which alters the partial pressure in the system to control the absorption of the refrigerant.

Diagram:

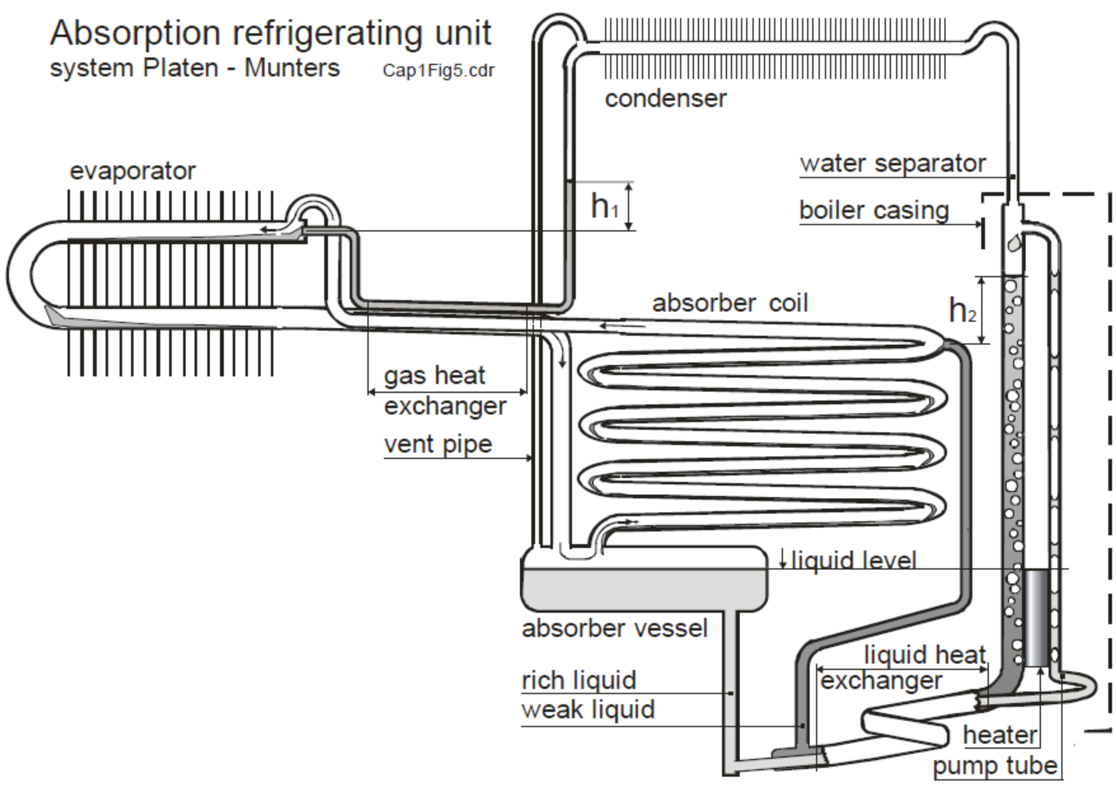

Figure 28: Platen-Munters Refrigeration System, Source (Almén, n.d.)

Working:

The entire system shown above is charged with three fluids. The water-ammonia solution and hydrogen gas which is inert. The entire system operates at a single overall pressure except for those pressure differentials which are the result of the liquid columns.

The condenser is positioned at a height which is higher than the evaporator so as to allow gravity flow of condensate. The height differential h_1 is not due to obstruction but because the temperature differential (left side tube at a lower temperature than the right side tube) causes a density differential (left side tube having greater fluid density) which is compensated for by the extra liquid column height h_1 in the right side tube.

Ammonia in liquid state enters the evaporator and the tube in the evaporator contains weak ammonia gas which is only fractional compared to the hydrogen volume available. The ammonia refrigerant evaporates into the gas by absorbing heat. This causes the density of the gas mixture to rise as ammonia vapour is several times heavier than hydrogen resulting in its natural flow down into the absorber.

Weakened solution at the outlet of the boiler is allowed to enter the top of the absorber coil where it flows into the absorber through gravity. This absorbs ammonia vapour from the gas which becomes lighter and flows upwards to the evaporator thus establishing a gas loop between the absorber and the evaporator which is one of the critical working points of the Platen-Munters Cycle.

The above interaction results in rich ammonia solution entering the absorber through the bottom of the absorber coil into the absorber vessel. This rich solution must again be regenerated through the addition of heat energy at the bubble pump. The flow to the bubble pump is established by the liquid head level in the absorber vessel.

The bubble pump heats the rich solution with a suitably placed heat source which results in the formation of vapour rich bubbles. These are similar to air lift pumps and the bubbles transport the vapour and associate fluid slugs upwards along narrow tubes. This pump is therefore known as the thermo-syphon pump. At the top of these narrow tubes, ammonia gas travels to the condenser and consequently into the evaporator.

There is an insulated part of the tube that acts as a water separator and the remaining liquid weak solution settles into a column that is connected to the top of the absorber coil. The flow of weak solution from this column to the top of the absorber coil is established by liquid head. The height differential h_2 is solely due to the temperature and consequent density differential. This occurs due to a liquid heat exchanger at the bottom of the unit to exchange heat between the ammonia rich solution going into the bubble pump and the weak solution exiting the bubble pump. The ammonia rich solution is heated while the weak ammonia solution is cooled down.

Another heat exchanger in place to improve the efficiency interacts with the hydrogen loop. As the hydrogen gas passes through the absorber it heats up and when it reaches the evaporator, it cools down again resulting in significant temperature extremes being experienced within the cycle. This alternative heat-cool cycle causes very high efficiency loss and the heat exchanger between the evaporator and the hydrogen helps to reduce these losses.

Prior to first operation, hydrogen is present in all parts of the system. As the bubble pump unit starts causing the flow of ammonia vapour, hydrogen evacuates from the boiler to the condenser, evaporator and through the vent pipe to the absorber and the overall system pressure increases slightly. When the ambient conditions have lower temperature, the condensers capacity to hold some residual hydrogen will be greater resulting in some of the hydrogen lingering in the unit. On the other hand, when the temperature is higher, all vapour cannot be condensed in the boiler and the vent pipe in the condenser transports the vapour back to the absorber.

The entire process therefore is solely driven on heat completely eliminating the need for any work driven component in the cycle. The elimination of this compression work increases the COP of the cycle again and the Platen-Munters cycle is purely driven by heat.

Another refrigeration system that works on diffusion absorption is the Einstein refrigeration cycle.

2.5.3 Vapour Adsorption Refrigeration (Heat driven cycle):

The vapour adsorption refrigeration system works similar in principle to the vapour absorption refrigeration system.

Adsorption is the process by which a fluid (liquid or gas) molecule attaches itself to a solid matrix. This constraint results in the liberation of energy as heat and the process of adsorption is therefore exothermic. The solid material that adsorbs the fluid is known as the adsorbent and the fluid is known as the adsorbate.

Diagram:

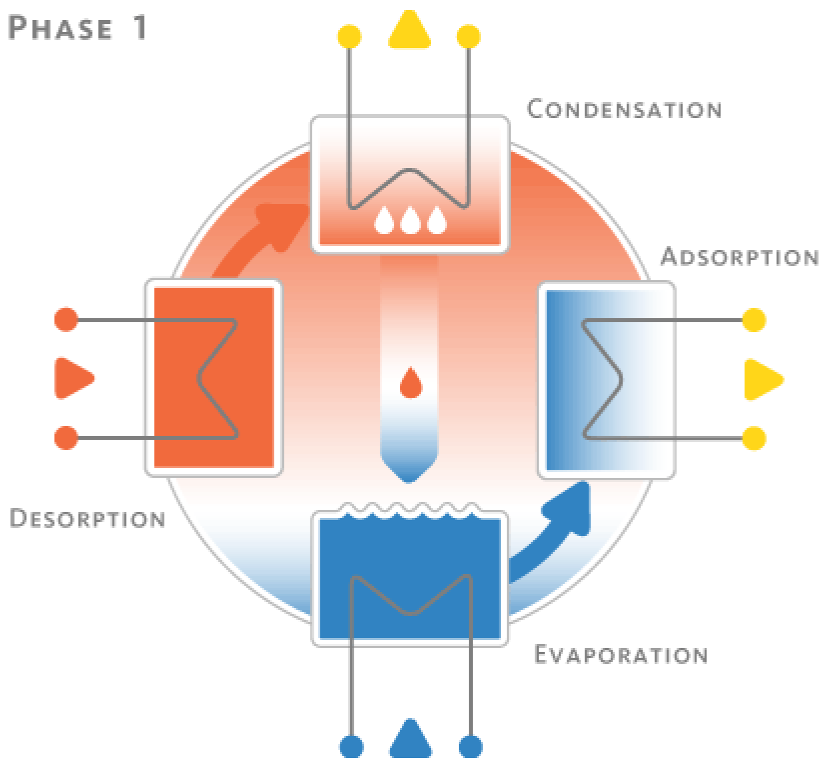

Figure 29: Adsorption Process – Phase 1, Source (InvenSor, 2012)

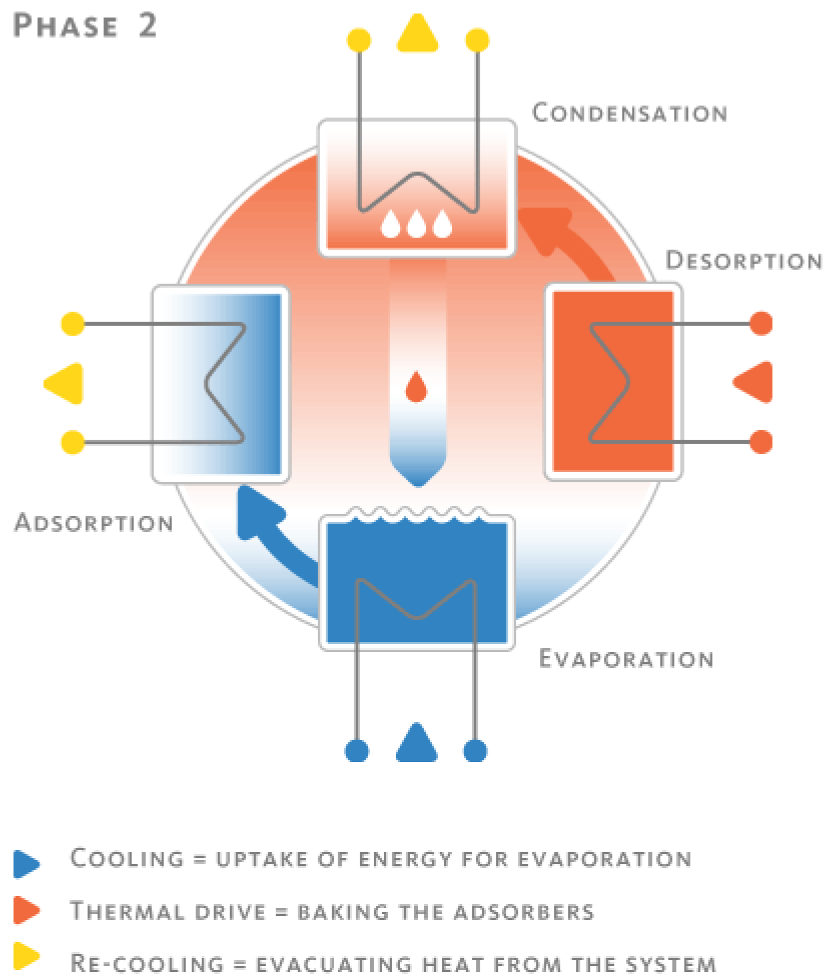

Figure 30: Adsorption Process – Phase 2, Source (InvenSor, 2012)

The refrigeration system consists of two adsorber beds, a condenser and an evaporator.

Consider the adsorption process starting with the heating of one of the adsorber beds which has adsorbed refrigerant. The heating causes the system pressure to rise as a result of the temperature increase. This is the equivalent of the compression process and the refrigerant is raised to the pressure-temperature condition of the condensation segment of the refrigeration process.

Further heating results in desorption of the refrigerant from the adsorbent bed which travels to the condenser where it releases excess heat to the surroundings in the condensation process.

The condensed refrigerant is then sent to the evaporation pressure after suitable throttling where it absorbs heat. The refrigerant in the evaporator evaporates by extracting heat from the space to be refrigerated and is again adsorbed by the second adsorbent bed.

The cycle is then repeated by heating the second adsorbent bed.

The heat of adsorption and the heat at the condenser need to be constantly removed in order to maintain the efficient functioning of the system.

2.5.4 Thermo-electric Refrigeration

In 1834, Jean Peltier discovered that when a current was passed through a cicrcuit of two dissimilar metals, one junction would cool down while the other heated up based on the direction of current flow. This is known as the peltier effect and is shown in the figure below:

Figure 31: Peltier Effect, Source (Cengel & Boles, 2006, p.636)

The COP of this system in comparison with the vapour compression cycle is very low, however, improvements are being made by utilizing different material combinations. Shown below is a more practical construct using semi-conductors:

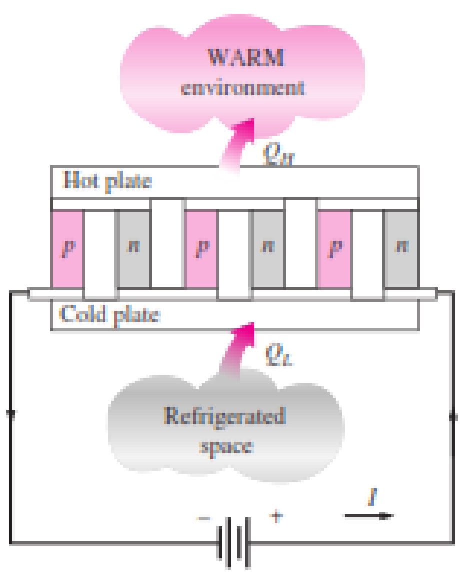

Figure 32: Practical Thermo-electrical Refrigeration Schematic, Source (Cengel & Boles, 2006, p.636)

2.5.5 Magnetic Refrigeration

Magnetic refrigeration, also known as adiabatic demagnetization works on the magneto-caloric effect which is a property that is intrinsic to magnetic solids. A paramagnetic salt acts as the refrigerant.

The application of a strong magnetic field aligns the atomic dipoles restricting degrees of freedom. In order to maintain this lower state of entropy under the external influence of the field, the salt releases excess energy as heat to a heat sink.

The thermal sink is removed and the field is removed. This results in the material having the capacity to absorb heat as it is now at a lower temperature due to heat loss.

As only a few materials exhibit the needed properties at room temperature, applications are generally limited to research and cryogenics.

3 Solar Insolation – The Indian Scenario

3.1 Solar Radiation and the Earth's Solar Energy Budget

A square meter of surface normal to the sun at the earth's upper atmosphere receives approximately 1.361 kW/m^2 of solar radiation (Kopp & Lean, 2011). The following figure is a visual graphic of the earth's solar energy budget as the solar insolation enters the atmosphere:

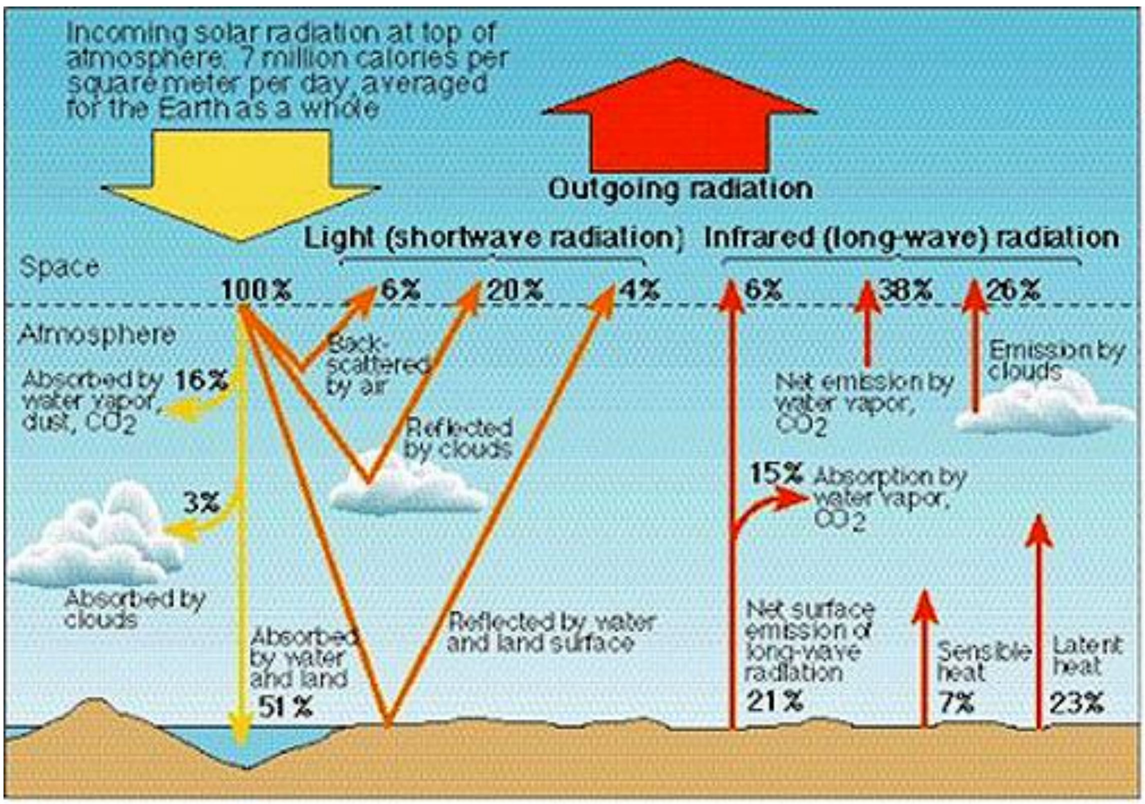

Figure 33: Earth's Solar Energy Budget, Source (Short)

3.2 Factors affecting availability of solar irradiation:

The earth's declination (and solar altitude)

The elliptical nature of the earth's orbit, one end of the orbit being closer to the sun than the other is the single most important factor that determines the amount of solar radiation at the upper atmosphere. This therefore varies throughout the year.

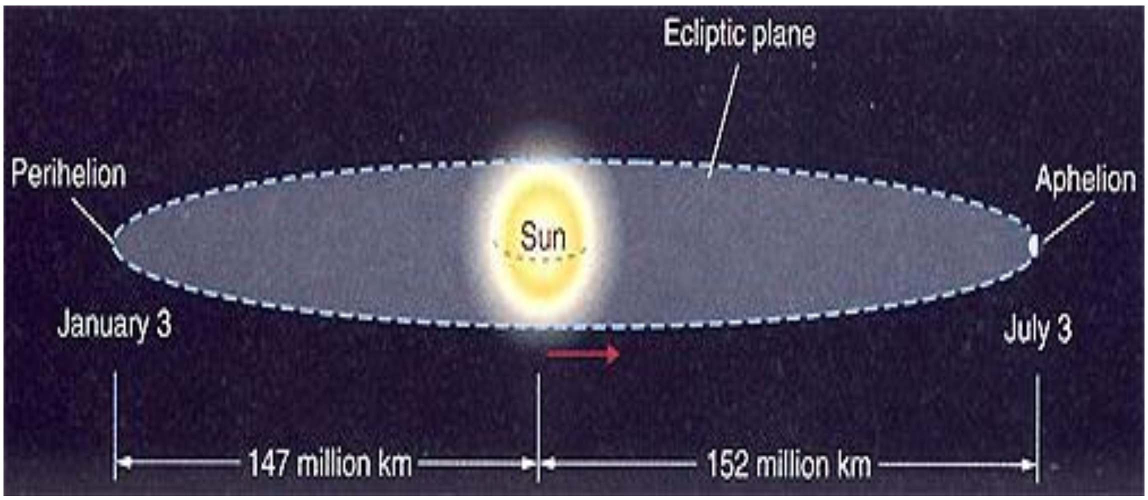

Figure 34: Orbital Eccentricity, Source (Short)

The declination, on the other hand, is the angle between the earth's equatorial plane and the orbital plane. While the axis of rotation of the earth is tilted at a fixed angle of 23.45 Degrees, the revolution of the earth around the sun results in the maximum radiation being received by the earth alternating between the tropic of cancer and the tropic of Capricorn through the year.

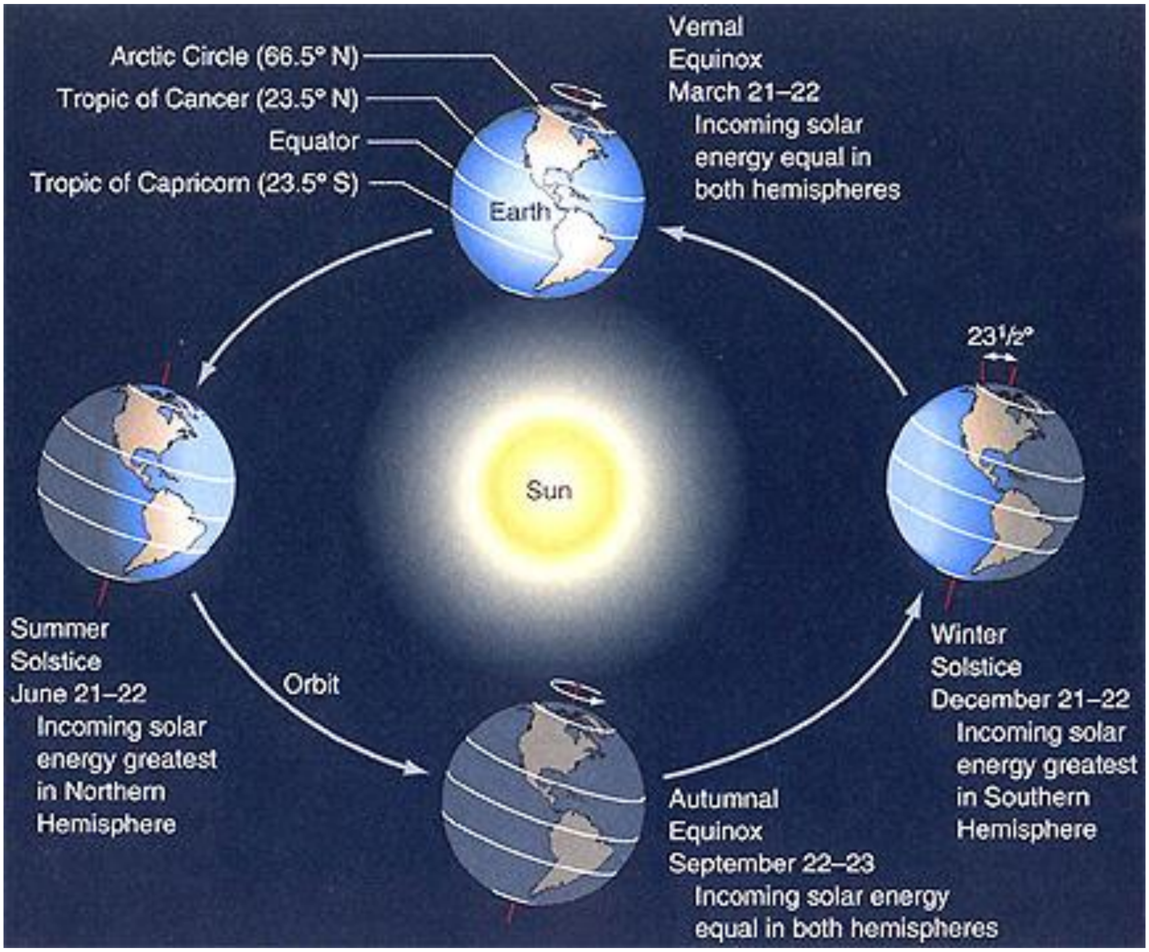

Figure 35: Seasonal Variation in Insolation due to Declination, Source (Short)

This causes:

- the seasons itself and results in a seasonal cycle in the amount of incident radiation available between summer and winter. The further away from the apparent equator a place is, the more atmospheric mass the solar radiation will have to travel through and also the greater is the spread of energy on the ground.

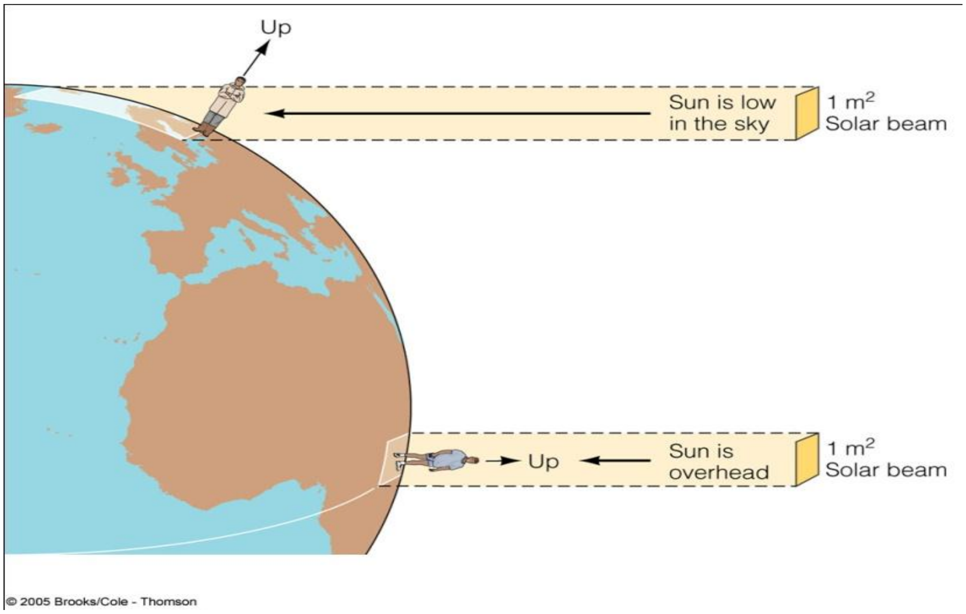

Figure 36: Solar Radiation and Air Mass, Source[5]

The atmosphere changes the whole spectral distribution. Most of the high-energy wavelengths are filtered out by the ozone layer. Generally, with longer paths through the atmosphere (at higher latitudes or around sunrise or sunset), the larger the part of infrared light, the low energy spectrum only gets through to the ground. This filter effect can be expressed by a turbidity factor (Green Rhino Energy, 2012).

- The above mentioned tilt/revolution/declination is the reason why places further removed from the equator will have longer nights and shorter days in winter and vice-versa in summer. (It is the reason for varying solar altitude between seasons). The optimal positioning of the solar collectors and solar PV panels is dependent on this and is important to the thermal collection / electrical generation and load matching.

[5] Available at - http://science.kennesaw.edu/~jdirnber/oceanography/LecuturesOceanogr/LecCurrents/0804.jpg (Accessed 24 July 2012)

The below image indicates the time of sunrise and sunset and the location with respect to a point on the ground for a latitude of 40 Deg North. The winters will thus have a lower sun (and consequently radiation sees a higher air mass also with greater energy spread and therefore lower intensity).

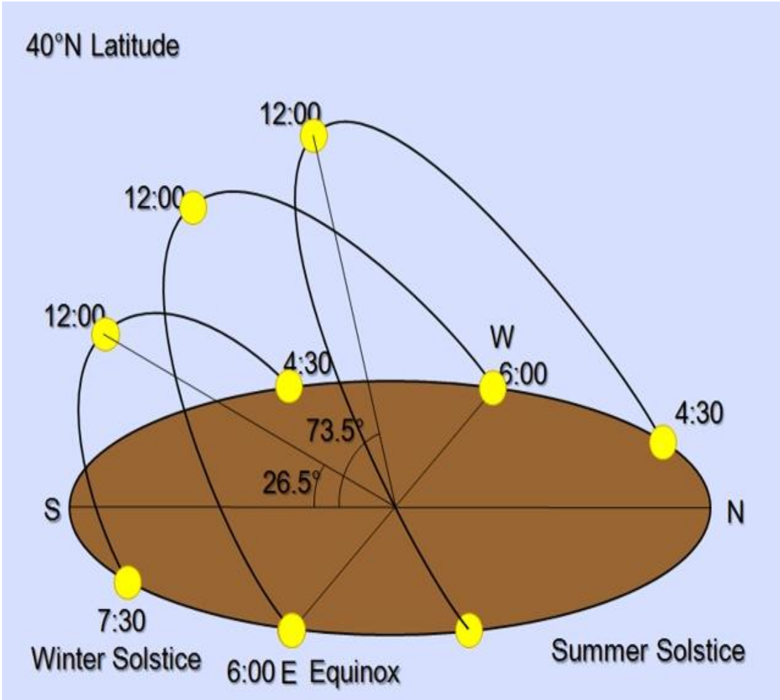

Figure 37: Solar Altitude, Source[6]

Other factors include:

- the local conditions which affect the optical properties such as visibility of the atmosphere. This can be affected by clouds, smog, suspended dust etc.
- local obstructions and shading.
- Orientation of solar collector or PV panel

[6] Available at - http://facweb.bhc.edu/academics/science/harwoodr/geog106/study/Images/AngleofInsolation.jpg (Accessed on 27 July 2012)

3.3 Components of Solar Radiation:

There are 3 components of solar radiation, as illustrated in figure 1, that provide illuminance at a surface:

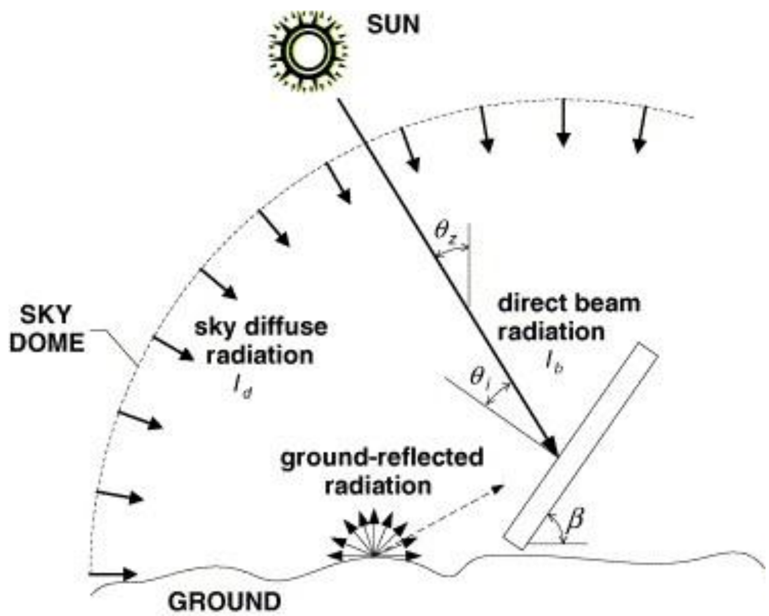

Figure 38: Components of Solar Radiation, Source (Thevenard & Haddad, 2006)

1. The direct beam component:

Direct beam radiation is point to point radiation from the sun directly to the panel.

2. The sky diffuse component:

This is the component of radiation which falls on the PV as diffused radiation. Eg. On a cloudy day, or immediately before or after the sun rises or sets, there is still some amount of light even though the sun cannot be seen. This is because sunlight is scattered by the sky and is incident on the panel from many different directions unlike direct beam radiation.

3. The ground reflected component:

The component of the total solar radiation that is reflected off the ground is known as the ground reflected component.

3.4 The Indian Scenario

Ramachandran et. al, in their paper (2011) investigating the solar potential of India analysed and reported that nearly 60% of the entire country averages greater than 5 kWh/m^2/day in annual average global insolation.

The following image shows the average solar insolation across India:

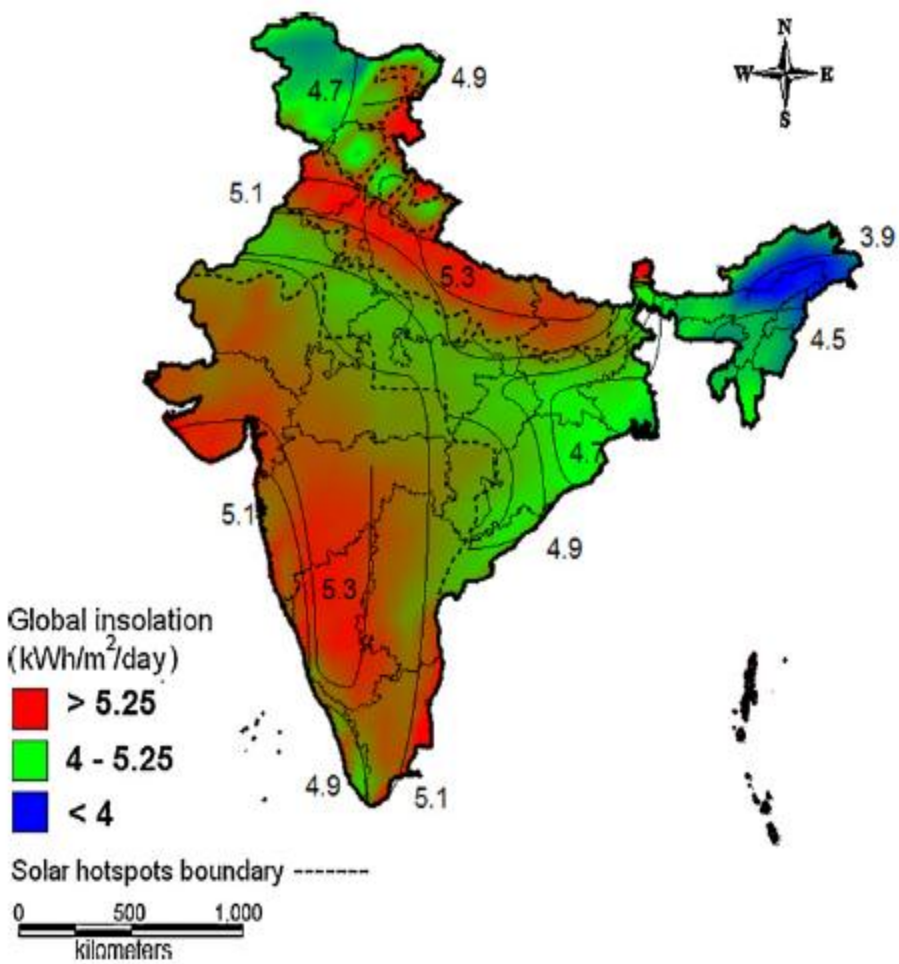

Figure 39:Annual Average Solar Insolation for India, Source (Ramachandran et al., 2011)

The following is an excerpt from the paper describing the pattern of solar insolation across the landscape across the various seasons.

“During the January (winter) month, major parts of the Southern Peninsula receive above 4.5 $kWh/m^2/day$ reaching a maximum of 5.5 $kWh/m^2/day$ in the Western Coast plains and Ghat regions, while the Western Himalayas in Northern India receives minimum of 2.5 $kWh/m^2/day$.

During February, a major expanse of the Indian landscape receives above 5 $kWh/m^2/day$ while the Western (Himachal Pradesh, Uttarakhand, Jammu Kashmir) and Eastern (Assam, Arunachal Pradesh, Nagaland) Himalayas continue receiving insolation in the range of 3–4 kWh/m2/day.

During April–May as the summer heat sets in, more than 90% of the country is seen to receive insolation above 5 $kWh/m^2/day$ with a maximum recorded 7.5 $kWh/m^2/day$ in the Western dry and Trans-Gangetic plains. During this period, the Eastern Himalayan region receives a minimum 4.7 $kWh/m^2/day$ global insolation.

With the onset of the summer monsoon throughout the country in June, there is a remarkable lowering of Global insolation towards the Southern (except for Tamil Nadu) and North Eastern ranges. The least recorded value in this period is 3.9 $kWh/m^2/day$. This trend continues till September as the summer monsoon recedes. The Northern part of the country remain minimally affected by this monsoon and is observed to receive higher values in the range of 5–7 $kWh/m^2/day$.

The Northeastern monsoon originating from Central Asia in October brings the Global insolation below 4 $kWh/m^2/day$ in the Lower-Gangetic plains, East Coast plains as well as the Northern most tip of the country. The Himalayan foothills, plains, Central Plateau and Western dry zones receive above 4.7 $kWh/m^2/day$ as the Himalayas act as a barrier to this winter monsoon and allows only dry winds to the Indian mainland.

With the arrival of winter by October end, the Northern to Western regions in India receive below 4.5 $kWh/m^2/day$ for about three months. "

"…the Gangetic plains (Trans, Middle and Upper) Plateau (Central, Western and Southern) region, Western dry region, Gujarat Plains and hill region as well as the West Coast plains and Ghat region receive annual Global insolation above 5 kWh/m2/day. These zones include major federal states of Karnataka, Gujarat, Andhra Pradesh, Maharashtra, Madhya Pradesh, Rajasthan, Tamil Nadu, Haryana, Punjab, Kerala, Bihar, Uttar Pradesh and Chattisgarh.

The Eastern part of Ladakh region (Jammu & Kashmir) and minor parts of Himachal Pradesh, Uttarakand and Sikkim which are located in the Himalayan belt also receive similar average Global insolation annually. "

For this reason of abundance in solar resource, the usage of solar energy is considered an appropriate opportunity to suitably utilize a renewable resource.

4 Pathways for Solar Refrigeration

The solar refrigeration system can be thought of as a combination of three primary subsystems.

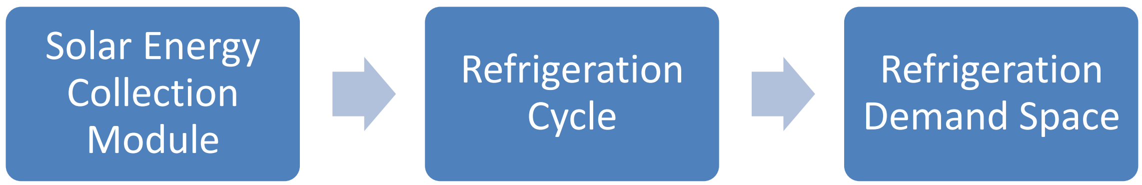

Figure 40: Solar Refrigeration System

There are two predominant pathways through which solar energy can be used for refrigeration.

1. Solar Photovoltaic
2. Solar Thermal

Shown in

Figure 41 below is an overview of the refrigeration processes using solar energy.

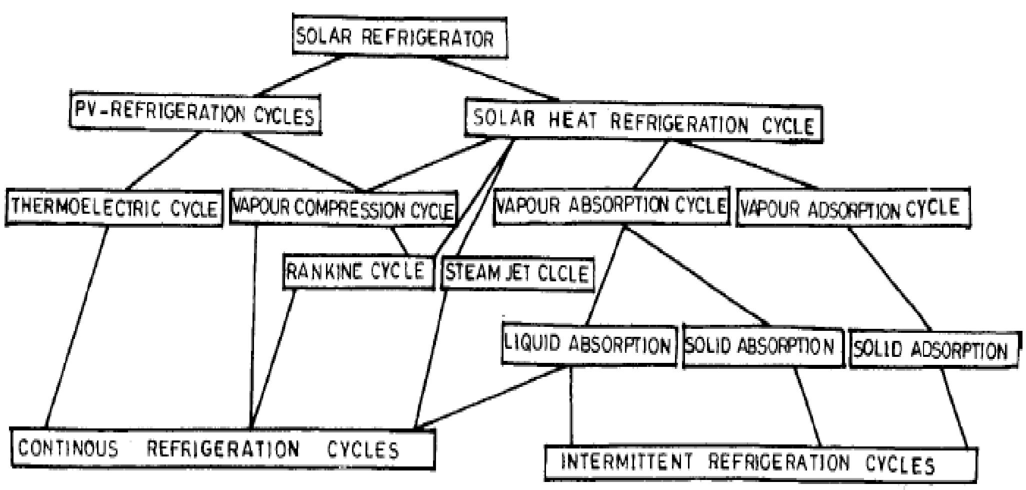

Figure 41: Pathways to Solar Refrigeration, Source (Anyanwu, 2004)

4.1 Overall Efficiency of Solar Refrigeration System

A meaningful comparison between the various solar refrigeration pathways can be drawn by ascertaining the overall system efficiency for each combination of the solar refrigeration options. This overall system efficiency is a function of the efficiency of both the solar energy collection system and the coefficient of performance of the refrigeration system. As a result of this The formula for the same is shown below.

Overall Efficiency = Solar Collector (or) PV Efficiency X COP Refrigeration Sys

Solar thermal collectors are efficient, in the region of 80% to 90% and above but the heat driven refrigeration cycles operating in tandem display lower COP. It should however be noted that the heat that can be supplied to a cycle is limited to nearly half this by the thermodynamic laws of efficiency which is based on source temperature caused by solar heating and the sink temperature which is the ambient temperature condition.

Solar Photovoltaic systems on the other hand have lower efficiencies typically around 10% and can be used to drive refrigeration systems with higher COP.

This tends to have a balancing out effect on the overall system efficiency in both cases.

4.2 Solar Photo-Voltaics

Solar Photo-Voltaic (PV) cells are devices that convert solar radiation to electricity using the photo-voltaic effect.

4.2.1 The Photovoltaic Effect

The photons in the radiation incident on the PV material cause the electrons within the valence band of the material (semiconductors suitably doped) to jump into the conduction band by the absorption of photon energy. This leads to the creation of electron-hole pairs. When the terminal nodes are suitably connected, the completed circuit allows for the migration of charge which is registered at the macroscopic level as direct current.

For useful applications, these electricity generating ‘cells’ are connected in series to provide a larger output voltage. These are normally referred to as strings. A set of strings form a PV module. A set of modules together constitute a PV panel and a set of panels together is called an array.

4.2.2 Types of PV Cells:

Mono-Crystalline PV Cells:

These are cells that are cut from a single crystal of silicon and are the most efficient and also the most expensive to produce. They are rigid and need to be mounted in a rigid frame to protect them.

Poly Crystalline PV Cells:

These cells are cut from a block of silicon, consisting of a large number of crystals. They are slightly less efficient and slightly less expensive than mono-crystalline cells and again need to be mounted in a rigid frame.

Amorphous type PV cells

These cells are manufactured by placing a thin film of amorphous (non crystalline) silicon onto a wide choice of surfaces. These are the least efficient and least expensive to produce of the three types. Due to the amorphous nature of the thin layer, it is flexible, and if manufactured on a flexible surface, the whole solar panel can be flexible.

4.2.3 General Construction of PV laminates:

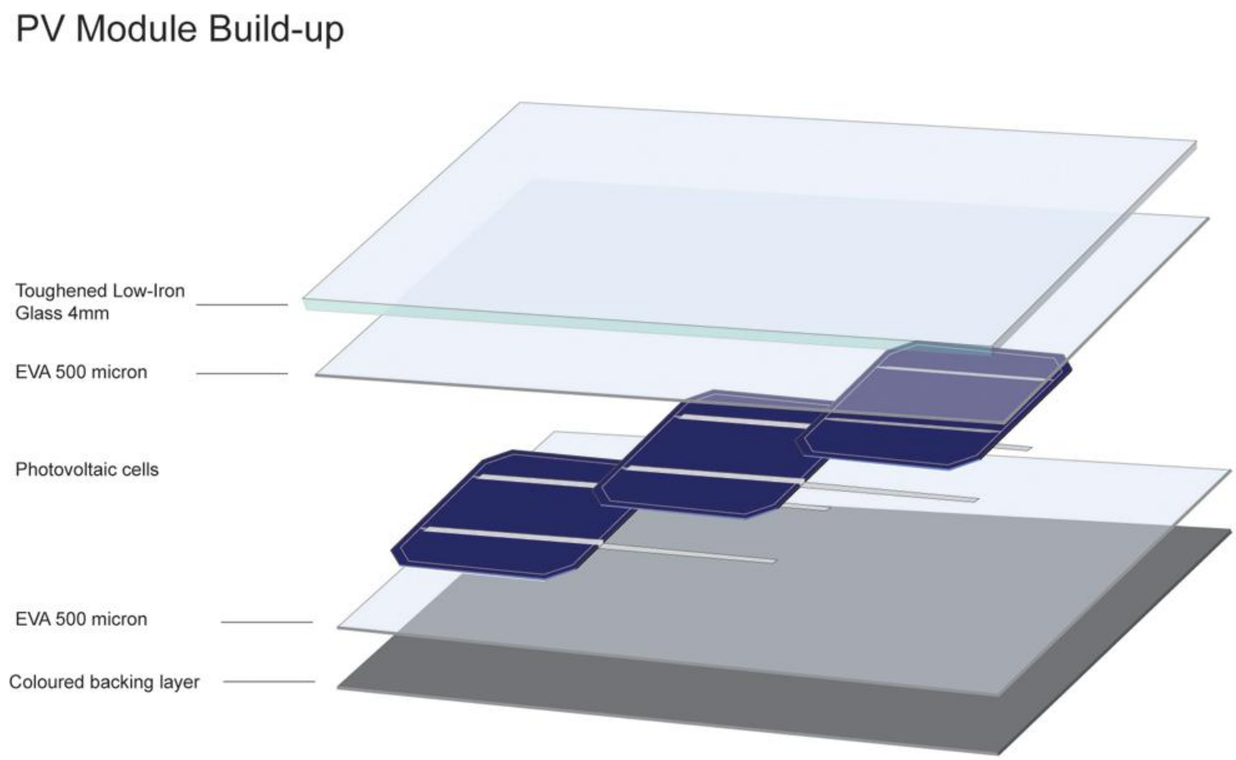

Figure 42: Solar PV – Laminate Construction, Source[7]

The figure above depicts the general construction of a solar cell.

The construction has to ensure the following:

- Provide structural integrity during the lifecyle of the cells

- Provide shielding against weathering elements

- Ensure maximum optical coupling between the transmitting layers and the incident solar radiation

- Provide electrical isolation in the interest of cell performance and safety

[7] Available at - http://www.viridiansolar.co.uk/Assets/Images/Technical/ (Accessed on 27 July 2012

When radiation is incident on a surface, it may be reflected by the surface, get absorbed within the surface or get transmitted through the surface. The reflectivity, absorbtivity and transmissivity for materials used throughout the transparent layers of the PV panel are of prime importance. For any material, these are represented as the fractions of the total incident light that they reflect, absorb or transmit.

reflectivity + absorbtivity + transmissivity = 1

It must however be remembered that these fractions for any given material is varies with the frequency of the incident radiation.

4.2.4 Solar Radiation Spectra for Solar Photovoltaics

The energy from the sun is spread over the electromagnetic spectrum from ultra violet to infrared. PV cells convert only a fraction of the total radiant energy. This is shown in the figure below:

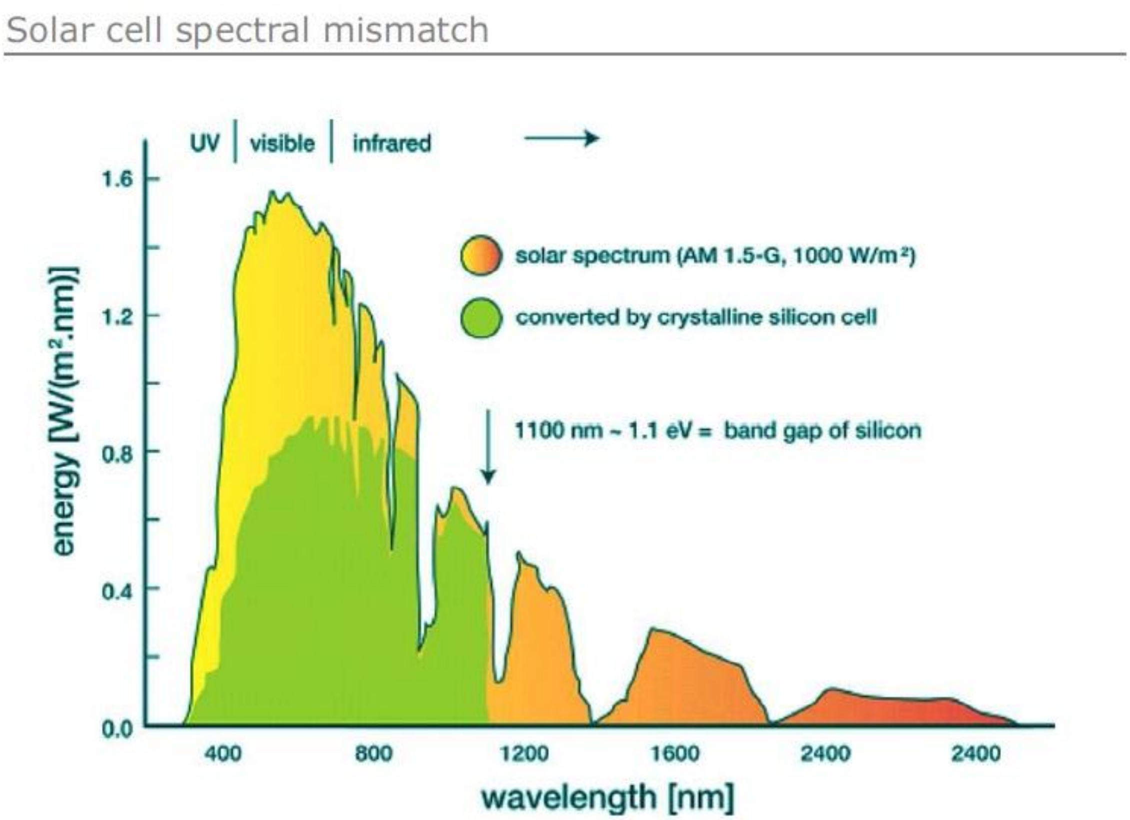

Figure 43: Solar Spectrum, Source[8]

It can thus be seen that typical cells generally respond to the shorter wavelengths of radiation.

[8] Available at

http://w3.uniroma1.it/nanophotonic/Presentations/Roberto%20Fusco.pdf

(Accessed in 2011)

In order to be able to compare solar modules, standard test conditions have been designed. These conditions include spectrum, intensity and temperature. The standard spectra refer to generic locations. They are prefixed “AM”, which stands for “Air Mass” and followed by a number, which refers to the length of the path through the atmosphere in relation to the shortest length if the sun was in the apex. It is approximated by

$$AM = \frac{1}{\cos(\theta)}$$ with the zenith angle θ. (‘theta’ is the latitude angle)[9]

[9] Available at http://www.greenrhinoenergy.com/solar/radiation/spectra.php (Accessed on July 24, 2012)

4.2.5 PV Panel Efficiency and Performance

There are a few factors that are used to characterize the performance of a solar cell (POSHARP, 2012). They are as listed below:

Panel Efficiency (%):

It is the ratio of output electrical power to input solar irradiation power for a given area of cell.

Maximum Rated Power Pm (Watt):

The maximum power output from a PV panel at STC.

The actual power from a cell can be estimated by

$$P_{real} = P_m * S / 1000 * [1 - \lambda(T_{cell} - 25)]$$

$$T_{cell} = T_{ambient} + S / 800 * (T_{NOCT} - 20)$$

where

S - Solar radiation on the panel surface [W]

$T_{ambient}$ - Ambient temperature [Deg C]

T_{NOCT} - Nominal Operating Cell Temperature [Deg C]

λ - Maximum Power Temperature Coefficient

STC – Standard Testing Conditions:

Each PV panel is rated using STC of solar irradiance of 1,000 W/m² at 0 incidence angle, a solar spectrum factor of 1.5 air mass and a temperature of 25°C cell.

Electrical Characteristics:

<u>Maximum Power Voltage Vmp:</u>

The voltage where a panel outputs the maximum power

<u>Maximum Power Current Imp:</u>

It is the maximum amperage for which a panel outputs the maximum power.

<u>Short-Circuit Current Isc:</u>

The maximum amperage generated by a PV panel exposed to sunlight with the output terminals shorted.

<u>Fill Factor (%):</u>

The ratio of actual rated maximum power Pm to the theoretical (not actually obtainable) maximum power (I_{sc} x V_{oc})

<u>Temperature Coefficients for voltage & current (power):</u>

There are also temperature coefficients for voltage and power which when applied can be used to estimate the voltage and power variation with respect to various temperatures.

4.3 Solar Thermal Collectors

A solar thermal collector is a device used to capture heat or thermal energy from solar radiation.

4.3.1 Type of solar collectors:

Solar thermal collectors can essentially be categorized as non-concentrating or concentrating. “A non-concentrating collector has the same area for intercepting and for absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux.” (Kalogirou, 2004, p.240)

An illustration of the classification of the collectors as taken from literature (Tyagi et al., 2012) and (Selvakumar & Barshilia, 2012) is given below:

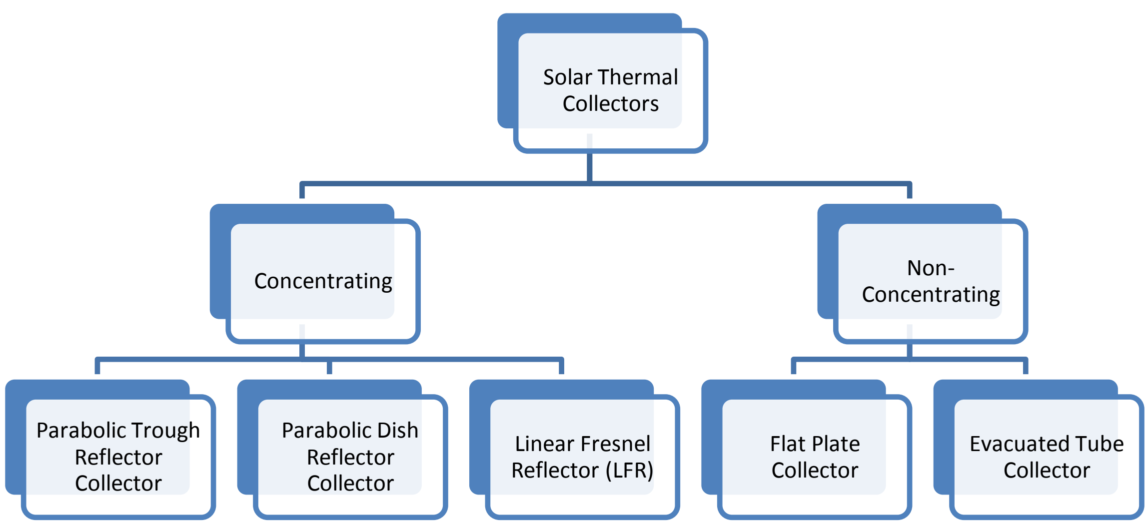

Figure 44: Solar Thermal Collectors Classification Source (Tyagi et al., 2012), (Selvakumar & Barshilia, 2012)

4.3.2 Concentration Ratio:

The concentration ratio is defined as the ratio of the area of the aperture to that of the absorber/receiver of the collector.

4.3.3 Concentrating type collectors:

The essential principle of concentrating type reflectors as mentioned above is the usage of a larger collection area to increase the focus onto a smaller absorber area. This therefore serves to increase the radiation flux on the smaller area and consequently produces higher temperatures.

Shapes such as the parabola have the ability to focus rays of light parallel to the axis of symmetry to a point.

This is shown below:

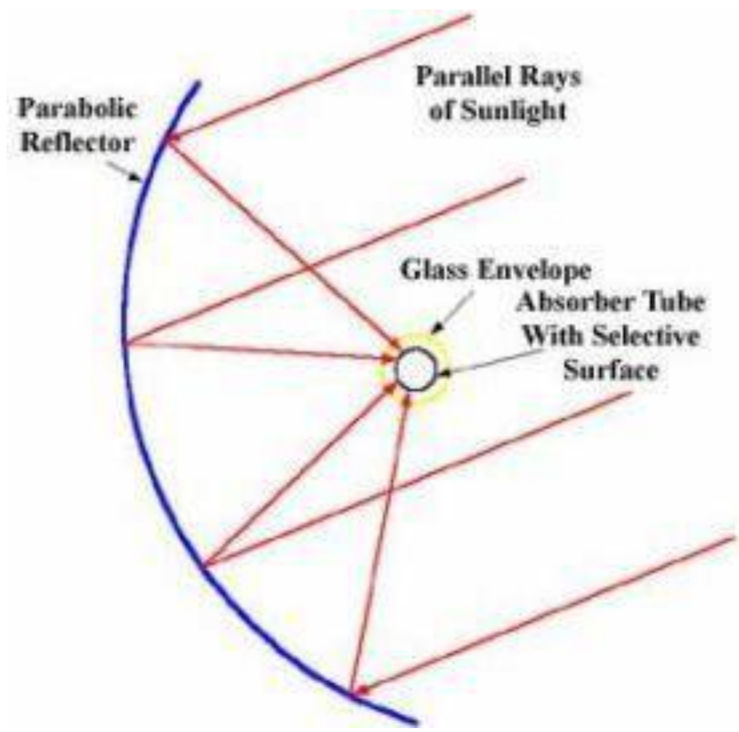

Figure 45: Parabolic Focus, Source (Alternative Energy Primer)

In general concentrating type solar collectors have certain advantages and disadvantages over non-concentrating type collectors (Kalogirou, 1998):

Advantages of concentrating type collectors:

1. Higher working fluid temperature translates into an increased thermodynamic efficiency
2. Higher temperature process tasks can be achieved with this
3. Lower heat loss at the absorber due to smaller area resulting in increased thermodynamic efficiency which can further be enhanced in an economical manner using techniques such as surface treatment and vacuum insulation (smaller area of absorber reduces cost)
4. Structurally less material in the collector required per unit of energy as compared to non-concentrating type collectors

Disadvantages of concentrating type collectors:

1. Concentrators capture very little diffuse radiation due to the lower size of the absorber
2. The focus onto a point is dependent on incoming rays being parallel to the axis of symmetry. It is therefore necessary to have a tracking system to follow the sun

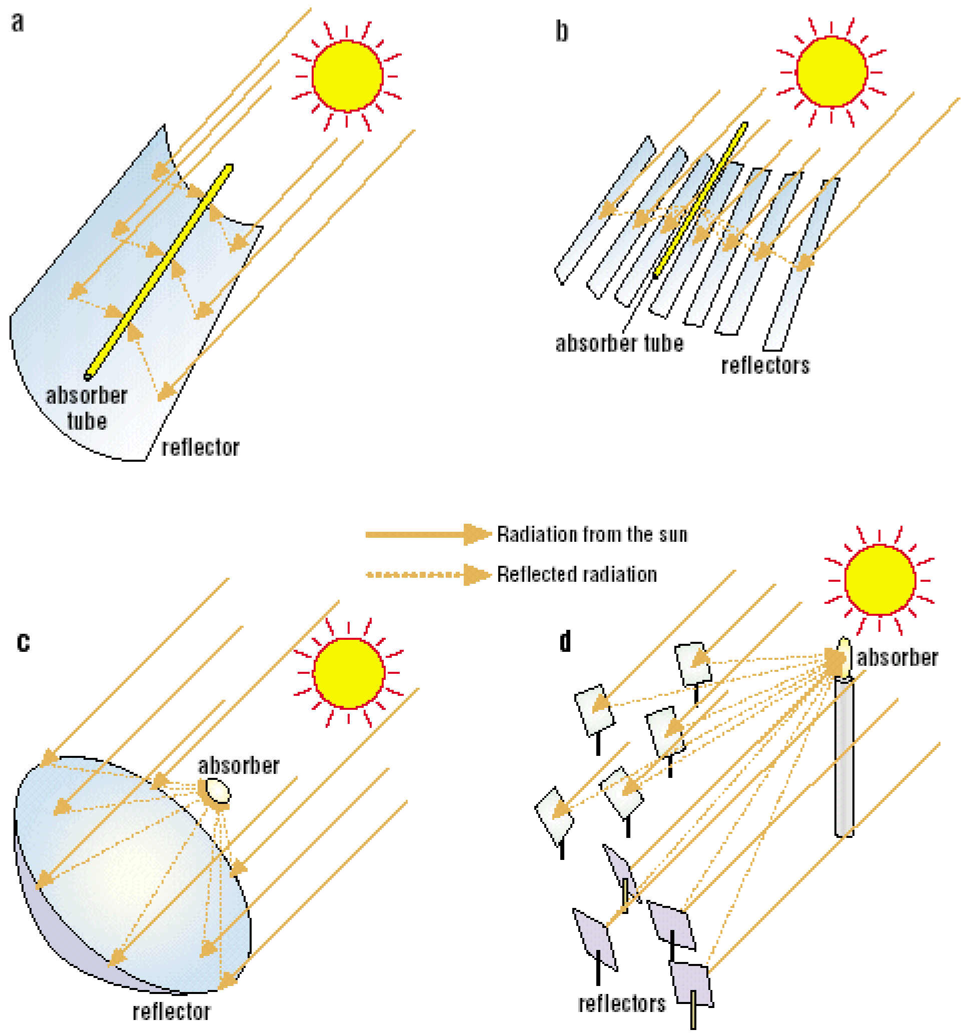

Figure 46: Types of Concentrating Solar Collectors, Source (Quaschning, 2003)

a. Parabolic Trough Collector (PTC)
b. Linear Fresnel Reflector Collector (LFR)
c. Dish Collector (PDC; P-Parabolic)
d. Heliostat collector

The figure above indicates some of the commonly employed geometries of the concentrating type collectors. There are however other concentrating collector variants that are used including such as lensing systems used to focus the light instead of reflectors.

All of these require tracking on one or two axis to follow the sun.

There is another concentrator known as the compound parabolic collector (CPC) which is kept stationary and provides concentration ratios above 1, but lesser than the ones with tracking.

4.3.4 Non-concentrating type

Flat plate collectors:

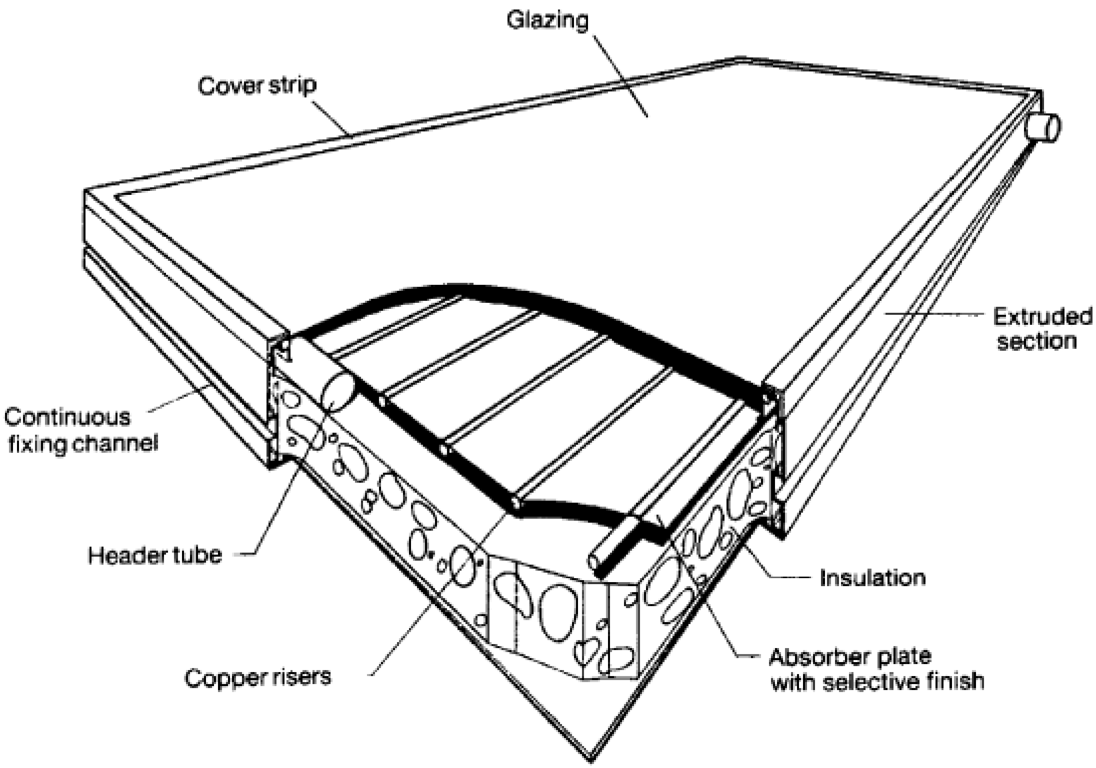

Figure 47: Flat Plate Solar Thermal Collector, Source (Kalogirou, 2004, p.241)

Flat plate collectors have the capacity to absorb diffuse components of solar radiation but have lower temperatures of operation. It essentially operates with working fluid being circulated through glazing covered containers where exposure to incoming solar radiation increases the temperature of the working fluid. These produce temperatures generally between 30 and 80 Deg C. They however have higher losses due to the greater area available for loss and non-insulation from convective losses.

Evacuated Tube Collectors:

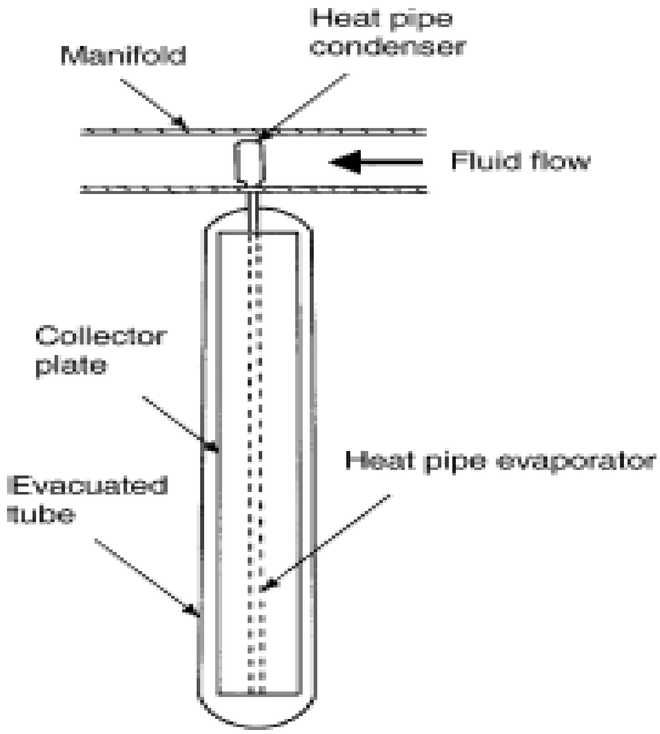

Figure 48: Evacuated Tube Solar Thermal Collector, Source (Kalogirou, 2004, p.246)

These type of collectors use evacuated tubes to reduce any convective losses. A series of these evacuated tubes are connected through a common manifold to achieve the required heat influx for a specific rate of flow. The temperatures achieved using these are higher and fall between 50 and 200 Deg C.

4.4 A Summary on Solar Collectors

The below table, summarises some of the commonly used collector types with an idea of the concentration ratios and the indicative temperature ranges that can be achieved (Kalogirou, 2004, p.241).

Table of Solar Thermal Collectors, Concentration Ratios and Indicative Temperature Outputs

Solar energy collectors

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat plate collector (FPC)	Flat	1	30–80
	Evacuated tube collector (ETC)	Flat	1	50–200
	Compound parabolic collector (CPC)	Tubular	1–5	60–240
Single-axis tracking			5–15	60–300
	Linear Fresnel reflector (LFR)	Tubular	10–40	60–250
	Parabolic trough collector (PTC)	Tubular	15–45	60–300
	Cylindrical trough collector (CTC)	Tubular	10–50	60–300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100–1000	100–500
	Heliostat field collector (HFC)	Point	100–1500	150–2000

Table 1: Solar Thermal Collectors, Concentration Ratios and Indicative Output Temperatures, Source (Kalogirou, 2004, p.241)

5 The Indian Analysis

The study of the solar hotspots in India by (Ramachandran et al., 2011) revealed the seasonal insolation patterns which have been tabulerized below:

Table 2: Monthly Variation of Solar Insolation Across India

SOLAR INSOLATION kWh / m2 / day				
	North	**East**	**West**	**South**
Jan	2.5 western himalayas	max 5.5	max 5.5	> 4.5 (5.5 in western coastal plains)
Feb	3 to 4 West and East Himalyas	> 5	> 5	> 5
Mar	> 3-4	>5	>5	>5
Apr	> 5 (4.7 min in East Himalayan region)	> 5	> 5	> 5 (7.5 in Trans-Gangetic Plains)
May	> 5 (4.7 min in East Himalayan Ranges)	> 5	> 5	> 5
Jun	> 5-7 (3.9 min North East Himalayan Ranges)	> 5	> 5	3.9 min (except tamil nadu)
Jul	> 5-7 (3.9 min North East Himalayan Ranges)	> 5	> 5	3.9 min (except tamil nadu)
Aug	> 5-7 (3.9 min North East Himalayan Ranges)	> 5	> 5	3.9 min (except tamil nadu)
Sep	> 5-7 (3.9 min North East Himalayan Ranges)	> 5	> 5	3.9 min (except tamil nadu)
Oct	< 4 (lower gangetic plain) -central latitudes	< 4	4-5.25	4-5.25
Nov	<4.5	4-5.25	<4.5	4-5.25 (except tamil nadu < 4)
Dec	<4.5	<4	<4.5	4-5.25 (except tamil nadu < 4)

The starting point for the investigation into solar power is based on a simple statement reported by (Ramachandran et al., 2011) that 58% of the country averages 5 kWh / m^2 / day on average annual in terms of global insolation.

The next significant step was a study of the comparison of various refrigeration technology pathways driven by solar energy. A doctoral thesis by Wimolsiri Pridasawas (2006) investigated the solar driven refrigeration systems at length. An indicative over view of the temperature capacity of the various solar refrigeration systems is seen from the diagram below.

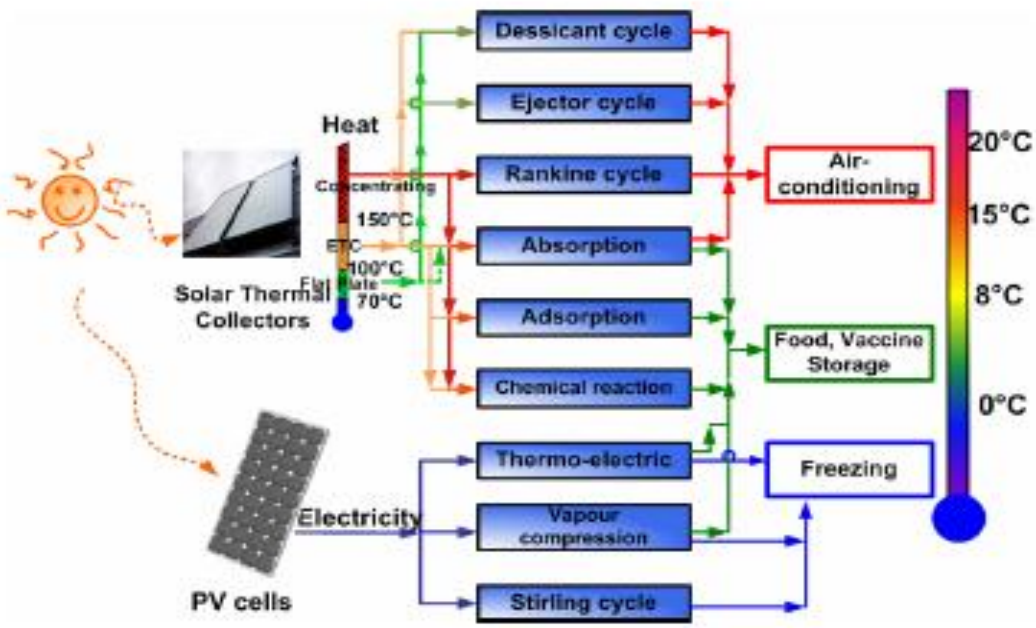

Figure 49: Refrigeration Pathway and Temperatures Achieved, Source (Pridasawas, 2006, p.40)

Another table summarizing the input temperatures, the respective COP's and their applications was helpful in summarizing the data. An extract from a book authored by Fléchon, J. et. al. "Guide to Solar Refrigerators for Remote Areas and Warm Countries" based the parameters on a 5 kWh / m^2 / day insolation region which is apt for the Indian scenario as detailed earlier in the thesis. This found that amongst the heat driven cycles for refrigeration, single effect absorption cycles have COP's between 0.6 and 0.8 which was higher than adsorption and chemical reaction systems with lower input temperatures between 80 and 190 Deg C as opposed to 80 and 300 Deg C and is further capable of ice production. These have been summarized and tabularized by (Pridasawas, 2006) and is shown below.

Table 3: Solar Refrigeration Pathways and Coefficients of Performance, Source (Pridasawas, 2006, p.53)

Refrigeration Cycle	Solar Technology		COP_{cycle}	Available Applications Today		
	Thermal Collectors (Tgen./ Tre-gen (°C))	PV Cells (Power for 30 L Cooling Box (W)		Refrig-eration	A/C	Example Applications
Electricity/Work Driven Cycles						
Vapour-compression		✓ (16-40)	3-5	✓		HR, SR, CB
Thermo-electric		✓ (a few mW)	0.5^{a}	✓		VT, CB, CT
Stirling		✓ (8-50)	3^{b}	✓		CB, LT
Heat Driven Cycles						
Absorption	✓ (80-190)		0.6-0.8 (single stage)	✓	✓	AC, IP
Adsorption	✓ (80-300)		0.3-0.8	✓		CB, IP, VS
Chemical re-action	✓ (80-300)		$0.1\text{-}0.2^{a}$	✓		IP, VS, FS
Duplex-Rankine	✓ (>120)		$0.3\text{-}0.5^{b}$		✓	AC
Desiccant cooling	✓ (40-80)		0.5-1.5		✓	AC
Ejector	✓ (80-150)		0.3-0.8		✓	AC

Remark
a: Fléchon, Lazzarin et al., 1999, based on 5 kWh m^{-2} day^{-1} of the solar radiation, b: Gordon and Ng, 2000., AC: Air-Conditioning CB: Cooling Box, CT: Car, Transportation, FS: Food Storage, IP: Ice Production, HR: Household Refrigerator, LT: Low Temperature Applications, SR: Small Refrigerator VS: Vaccine Storage, VT: Vaccine Transportation

The rationale to investigate absorption cycles further was founded on this basis. A further comparative study in the same paper established the advantages of each refrigeration system.

Table 4: Tabular Comparison of Refrigeration Pathways, Source (Pridasawas, 2006, p.118)

Advantages	Disadvantages
Absorption Systems	
• Only one moving part (pump) with the possibly of no moving parts for small systems (e.g. Platen-Munters cycle) • Possible to utilise low-temperature heat supply	• It cannot achieve a very low evaporating temperature in using LiBr-H_2O as working media. • The system is quite complicated and difficult for service.
Adsorption Systems	
• No moving parts (except valves) • Low operating temperatures can be achieved.	• The high weight and poor thermal conductivity of the adsorbent make it unsuitable to use for high capacities and can cause long-term problems. • Low operating pressure requirement makes it difficult to achieve air-tight • Very sensitive to low temperature especially the decreasing temperature during the night. • It is an intermittent system.
Chemical Reaction Systems	
• No moving parts • Low evaporation temperatures can be achieved.	• Low COP • High weight of adsorbent, not suitable to use for high capacities. • The system design is complex especially due to the volume of the adsorber that changes when chemical reaction occurs. • Low operating pressure at a lower temperature, difficult to achieve air-tightness.

Stirling/PV systems	
• Relatively high COP for high temperature lifts. • Can be used for cryogenic applications and is mechanically simpler than other applications for low temperature operations. • Environmentally friendly • Mobile and light weight	• High production costs • Complexity in design
Thermoelectric/PV systems	
• No working fluid and no moving parts (except fans) • Quiet • Small size and light weight	• Low COPs • Difficult to achieve a low refrigeration temperature • Low reliability especially when the power supply is cut off. • Requires efficient heat sink in order to reject heat from the thermo-electric module. • Not suitable for large cooling load • Induces thermal short circuiting when not operated
Vapour Compression/PV systems	
• High COP • Long term experience and widely available commercially • Scalable from small to a large systems	• For a PV system, installation cost is high and requires battery for energy backup. • Can be noisy.

In summary, the rationale between the choice of absorption cycle for further investigation was due to the following reasons:

- Its capacity to run on lower grade heat as opposed to vapour compression systems which require either electrical energy or higher grade heat to run more expensive thermo-mechanical refrigeration systems. This makes it apt for rural areas with high insolation levels.

- Its capacity to run at lower heat input temperatures than adsorption systems as captured in the tabular summary representing input temperatures and COP.

- Its capacity to chill down past 0 Deg C in order to form ice battery packs which can form thermal reservoirs as opposed to PV systems which require replacement of batteries on a frequent basis.

- The minimal moving parts in absorption cycles and consequently minimal maintenance cycles and lower failure rates are seen as favourable points.

- Its low weight and bulk to performance ratio compared to adsorption systems

- Its lower capital cost and no requirement of battery replacement (due to its capability to form ice storage batteries) compared to PV systems.

- Industry strength and documented experience with larger absorption systems have been established.

As suggested by Braun & Heb, one of the pressing requirements with absorption refrigeration is to scale these systems to mid-scale applications which are greater than a few 100 watts of application and lesser than 100 kW.

The decision to investigate this further was strengthened by another paper which was a state of the art review on solar refrigeration by D.S. Kim et al, (2008) produced such a comparison. The following image is an extract from the paper and is a comparison of various solar pathways based of course on certain assumptions. This is however indicative of an initial cost versus performance approach in solar refrigeration.

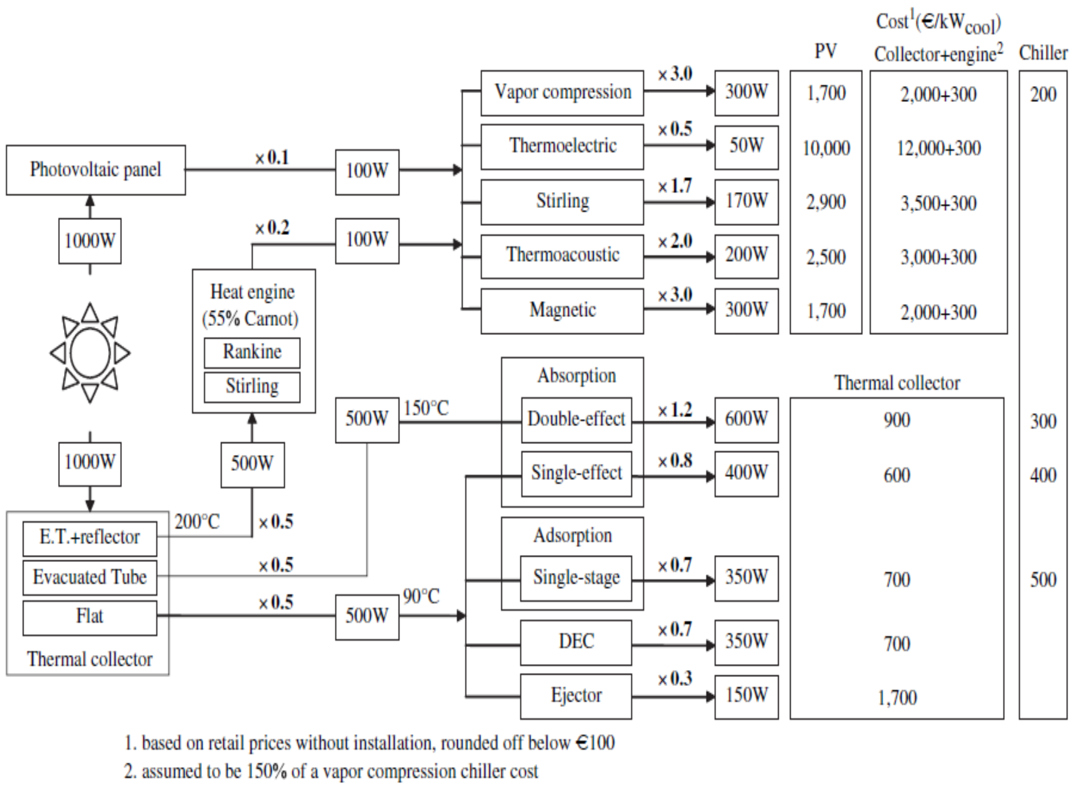

Figure 50: System Efficiency, COP & Cost / kw of Cooling For Various Solar Refrigeration Pathways, Source (Kim & Ferreira, 2008, p.12)

The 3 columns towards the right most end are indicative of specific costs for a unit of cooling. This includes Solar PV costs, Solar Collector cost for engines, engine costs, chiller costs and thermal collector costs.

The costs of chillers were based on the smallest units available as they vary significantly in cooling capacity. The efficiencies of the solar collectors are indicative. It is noted that this is dependent on both ambient temperature and solar radiation. As India sees moderate to high temperatures and significant solar insolation, the above assumptions were considered practical for a baseline. The solar electrical systems are assumed to have an efficiency of nearly 10%. Solar collector efficiencies are assumed at 50% for 200 Deg C. While the second law efficiency places a limitation on this at 56%, the heat engine efficiency is assumed at a lower 20% and as this is a conservative measure is still considered appropriate for relative grading of the technologies.

Solar photovoltaic and thermo-mechanical refrigeration systems were found to be significantly more expensive with the vapour compression system and magnetic refrigeration systems being the most attractive options in this pathway.

The conclusion of this study identified that solar thermal system in combination with single effect absorption refrigeration machine would be the best price option. This was followed closely by single effect adsorption machines and double effect absorption systems.

A different study was undertaken in order to determine the best solar thermal collection technology for electricity generation in north-west India receiving on average the Indian solar global insolation of nearly 5.5 kWh / m^2 / day. This paper published by Nixon, J.D. et al (2010) used the analytical hierarchy process to help in multi criteria decision analysis as the cost-benefit analysis was deemed far too simplistic. A comparative literature review of the solar thermal technologies was suitably extrapolated to the Indian case scenario. The criteria involved were broadly classified into technical, financial, environmental and scalability aspects. 4 case studies were presented to a panel of experts in order to determine optimum strategies for each context. This identified that for Gujarat in India, the linear Fresnel lens – compound parabolic collector was the optimum strategy with the compact linear Fresnel reflector being a close second (pp.5237, 5238). The weighting factor for the indian scenario that propelled Fresnel technology ahead of others is the cost criterion which placed them among the highest in the final grouping order (p.5238).

A snapshot of the analysis based on the weightings is given below

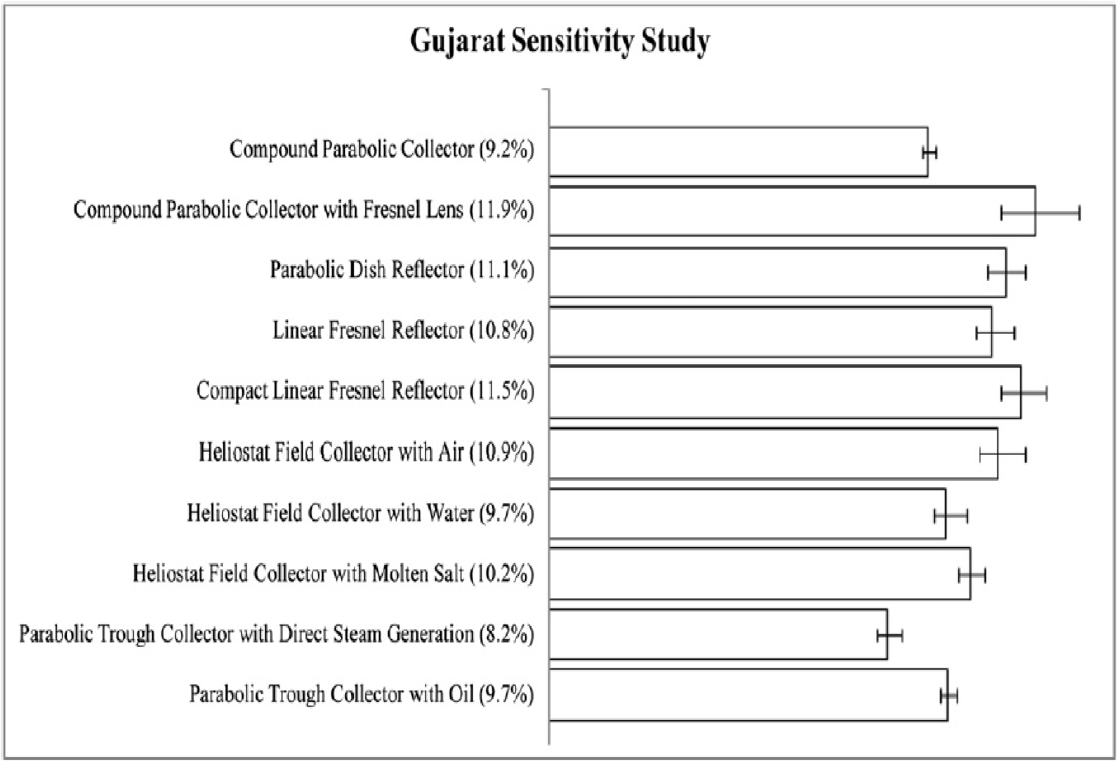

Figure 51: Solar Thermal Collector Comparison for the Indian ScenarioSource (Nixon et al., 2010, p.5237)

While the study has been done for field collectors, apart from the standard flat plate and evacuated tube technology, it is noted that these collectors are used for ice production in the solar refrigeration applications that have been devised thus far. Extensive literature such as papers by (Erickson, 2009), (Moreno-Quintanar et al., 2011), are available on this and it was therefore decided to include this analysis in the report as this forms one of the critical sub systems for solar refrigeration.

The issues to be tackled included

1) Cost effective availability of suitable real estate in more urbanized areas
2) Lack of reliable power in remote and remote parts of India

3) Availability of small to medium sized storage options for produce in all areas with suitable farm density
4) Availability of suitable transport mechanism to point of demand
5) High capital costs of cold storage infrastructure
6) Recurring costs of cold storage infrastructure
7) Improvement of capacity utilization of cold storage
8) Reduce environmental impact of cold chain

In order to deal with the each of these scenarios, a stepwise approach to preferred design was considered.

In order to tackle the requirement of cost effective availability of real estate, a cost effective solution catering to rural areas would be to locate smaller cold storage facilities for rural and remote farm clusters.

With regard to the lack of reliable power, alternative energy technologies would be ideal to investigate due to the rising price of fuel and lack of electrification. Out of the renewable forms of energy available, solar energy is ideal due to its geographical spread across the entire country round the year. This is not so in the case of wind, hydro or other renewable technologies which tend to be extremely site specific. Evidence supporting the choice of solar renewable energy is documented by Ramachandran et al. (2011) in their paper identifying that nearly 60% of the geographic expanse of the national is well catered to by solar energy.

The larger cold storage set ups are already being heavily supported by Government initiatives, subsidies and tax cesses, However, the larger capital outlay and lower return on investment is still a major roadblock to cold storage development. On the other hand smaller devices such as Godrej's Chotukool (Munuswamy, 2009), (Economic Times, 2011) priced at only Rs 3400 and 3700 (approximately $69) is doing extremely well in the market. Therefore, a solution that is small to medium in terms of storage was rationalized as a requirement which could help spread capital risk over the resources of a farm cluster or smaller agricultural cooperative.

With a choice between various solar driven refrigeration technologies, it was decided to consider single effect absorption systems with solar collectors(flat plate and evacuated tube) due to a lower price point (Kim & Ferreira, 2008). However, a further study would be needed into Fresnel lensing and compact Fresnel reflecting techniques which were found ideal for electricity generation and may have the potential to deliver quality heat for a greater period of time with suitable tracking technology. This would have to be done on a case by case basis across the geographical spread of India based on the cloud conditions and turbidity of the atmosphere however. Flat plates have a distinct advantage in that they are well capable of receiving scattered radiation and converting it into useful heat although at lower temperatures and lower rate of working fluid flow. The choice of heat driven refrigeration cycle is nevertheless considered ideal in a country with significant biomass reserves and currently investigation into this by institutes such The Energy and Resources Institute(TERI) are underway. TERI are working on a solar-biomass hybrid to meet refrigeration requirements in the country. It uses a 15 kW Vapour Absorption Refrigeration Machine and is expected to produce cooling for 25 tonnes of fruits and vegetables in cold storage. This concept utilizes Scheffler dishes, with 9.3 m^2 (2.5 kW) and 16 m^2 (5 kW) to achieve the focus of solar energy and are available at price points between Rs 85,000 and Rs 1,60,000 (PRINCE). Again, this system uses vapour absorption to provide the refrigeration and has the capacity to cool down to 0 Deg C in Indian ambient conditions making it possible to store a wide variety of produce (The Energy and Resources Institute, 2011), (Kumar, 2012).

An ideal aspect in design would be the usage of containerized refrigeration systems. This could later be used to integrate with the transportation system of the cold chain which is still undergoing development throughout the country. The current system only has a very few transportation players with 85% of the very fragmented industry being dedicated to cold storage facilities and only 15% of the companies into the transport cold chain (Kapoor et al., 2012, p.5). Containerization would therefore add mobility to the cold storage and systems standardized thus would be suitable for modular movement of produce.

The portability of containerized units would also allow for the allocation of containers to various locations in order to maximize the capacity utilization of the portable units. This would be a significant boon especially as the organized retail market can utilize this aspect of design to optimize their capital outlay and operations moving resources to areas where harvest is due. As per KPMG's analysis the organized retail market only forms 2% of the current Indian food industry as opposed to 65% in developed nations (2009, p.18). This would be a two pronged approach as this would increase the value of the produce and make the products suitable for export especially where cold chain continuity is expected while lowering the per use cost of the container system due to operational optimization. This would have the effect of improving the capacity utilization which is currently very poor as mentioned in the earlier sections of the thesis. In order to approach this for improvement in capacity utilization, an appropriate synchronization would need to be achieved with the crop calendar of that particular region. An example of the crop calendar is provided below.

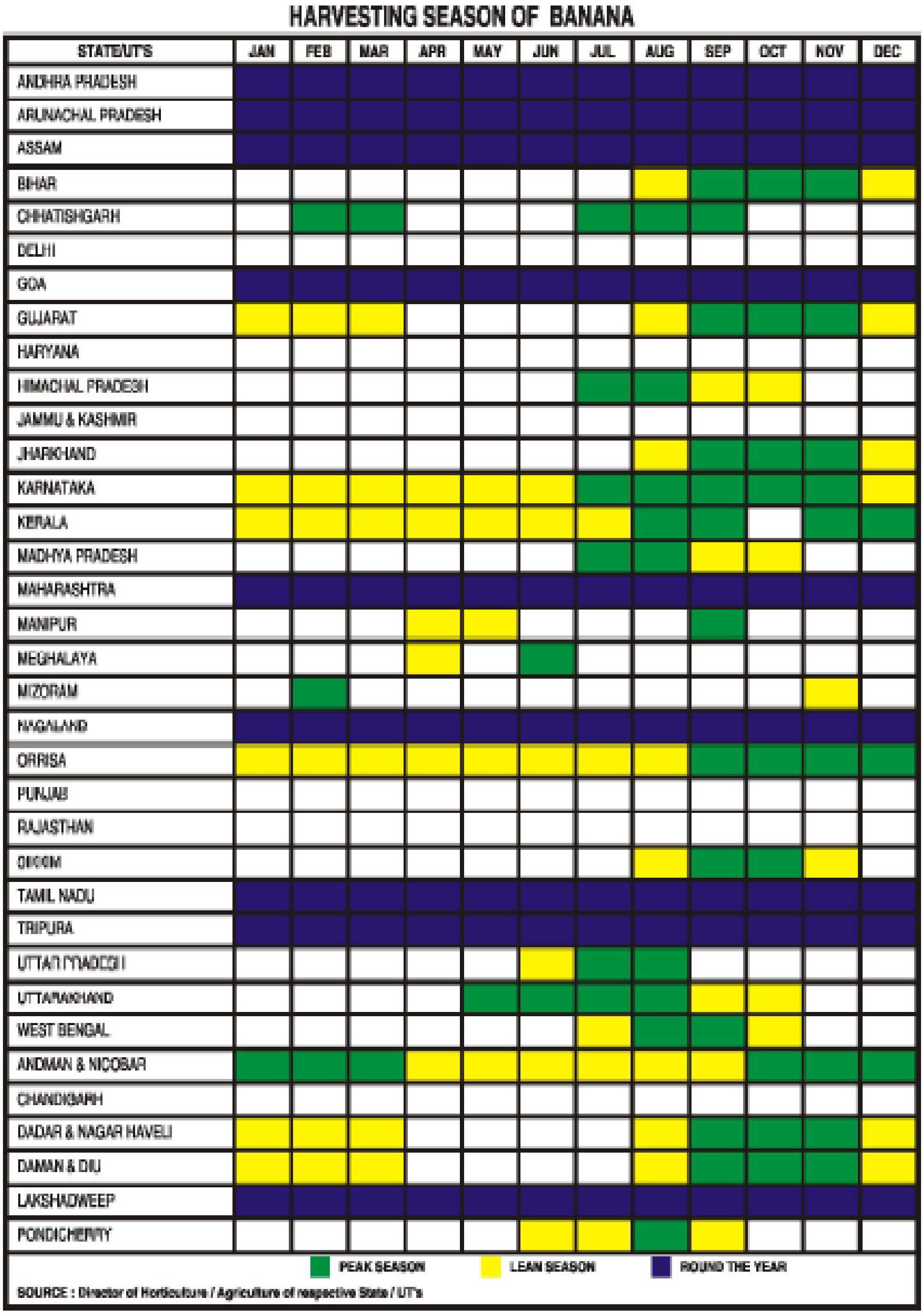

Figure 52, Banana Crop Calendar (National Horticulture Board, 2011, p.36)

This is indicative of the crop cycle across different states in the country. As the lean seasons and harvest seasons occur at different times in different regions while the solar insolation remains more or less ample (except during monsoon seasons) throughout allowing the suitable transfer of containerships across regions.

There are other studies that have converged on this design approach as well. A paper by (Maheshwar), a manager in fleet management submitted at the world energy council congress approached the same design albeit with solar panels to run conventional vapour compression based machinery. This was also adopted by the Sainsbury chain in the UK in a study with the University of Southampton to run a refrigerated trailer (Bahaj, 1998). Operational statistics were studied in a paper in 2000 (Bahaj, 2000). A second paper studying the data of the refrigeration system analysed the economics of the same for the UK market and found payback times of 15 years with the scope of reduction to 8 years (Bahaj & James, 2002). SunDazer designs for refrigerated transport also converge on similar design with a solar powered system (SunDazer).

This approach of using a heat driven cycle to drive refrigeration could utilize the waste heat derived from the engine of the transport system. This has been explored in several studies. Horuz in a study on “An Alternative Road Transport Refrigeration” (HORUZ, 1998) explored the option of using a vapour absorption refrigeration machine and found that it is indeed feasible with the need to explore further regarding the effects of back pressure on engine performance. It however removed the need for a dedicated IC engine to drive the compressor as is typical in vapour compression refrigeration machines. This served also to reduce the unit weight, capital cost, transport fuel cost and maintenance required to run these systems. Another more conclusive study was conducted by Michael A. Garrabrant in a study, the results of which are captured in a paper titled “Waste-Heat Driven Absorption Transport Refrigerator” (1999). The study reported that these systems have refrigeration capacities up to 11.1 kW utilizing the heat from exhaust gases through a hydronic heat exchanger coupled to the generator of the ammonia absorption system. Typical systems using the conventional vapour compression technology ranged from 5.9 kW to 14.6 kW. It can be seen from this that there is significant scope in utilizing waste heat from the exhaust gas of the transport system to drive refrigeration for the containership for produce with significant savings in fuel costs and satisfactory performance of the engine. This also serves to reduce the environmental impacts due to lower use of fossil fuels to transport the produce.

The next aspect to further suit this for rural areas would be the removal of any electro-mechanical input. There are two systems that are known to do this. One is the Platen-Munter's cycle and the second is the Einstein Refrigeration system. Essentially these are vapour absorption machines, however, the pressure in the system is not altered throughout removing the necessity for a pump. Although the absorption refrigeration systems are a significant improvement over the vapour compression systems due to the reduction in work required, the two above mentioned cycles use a different technique to bring about the refrigeration and heat dissipation effects and are known as diffusion absorption systems. Apart from the refrigerant, selective addition and removal of an inert gas alters the partial pressure of the refrigerant in various chambers such as the condenser and the evaporator causing the refrigerant to either condense or evaporate without the need for creating a pressure differential with an external pumping device. However, the necessity for a flow to occur is created with the help of a thermally driven bubble pump. An experimental study of the optimization of a bubble pump was carried out as part of a thesis by Susan Jennifer White (White, 2001). The study involved the optimization of heat energy input at the bubble pump to the thermally raised fluid mass which was used as an indicator of performance. Parameters that were altered included the submergence ratio which is the ratio of height of separation between the pumping and pumped into chamber and of course the diameter of the system. The similarities to air lift 2 phase flow models allowed the slug and churn flow regimes to be studied against previously defined equations to study the performance. It was found that the presence of slug flow optimized the model efficiency in mass transferred per unit of heat up the pump pipe. The model was then used to study an ammonia-water system where optimum diameters were found up to 0.02 kg/s of pumping rate. It was deduced that the increase in submergence ratio improved the efficiency of the system with values 0.8 in the submergence ratio yielding 0.53 kg of mass transfer per KJ of heat supplied. The optimization of this system can help yield better returns and this area needs to be investigated when bubble pump diffusion absorption refrigeration systems area being used.

While the system is on site, the refrigeration effect needs to be sustained when the sun is not shining and the possible pathways to this could be through battery packs (in the case of Solar thermal systems connected to heat engines), ice battery creation or maintaining the heat in on site thermal storage systems such as water or oil banks which can be used to provide thermal energy needed to run the absorption generator.

CASE STUDY

In a report by (Braun & Heb), an examination of two developed systems to store produce to temperatures as low as 4 Deg C is considered utilizing ice banks as suitable storage mechanisms.

The study was a two and a half year project funded by the Ministry of School and Further Education and Science and Research of the Federal State of North Rhine-Westphalia.

System 1

One of the systems was a larger, ammonia-water absorption system for a 60 kW refrigeration load with the requirement of 1 kWe electrical pumping energy to store fruits and vegetables at 4 Deg C driven by solar energy. This placed the storage floor area at 600 m^2 capable of loading 30 MT of fruit produce considering ambient conditions of 35 Deg C which are similar to Indian conditions. This also incorporated with it an ice battery or ice storage for phase change energy with a capacity of 300 kWh. Key features of this included the need for 200 m^2 of absorber area with vacuum tube solar collectors.

System 2

The second system studied was a smaller Platen-Munters diffusion absorption refrigeration system catering to a load of 1.2 kW running at a lower temperature level of -4 Deg C requiring about 2.4 kW of heat input to the bubble pump and generator. The system required a high performance vacuum tube solar thermal collector with 6.4 m^2 of absorber area with COP approaching 0.5 when heat output at the condenser and absorber was closer to 55 Deg C. This was to cater to 500 kg of fruit and vegetable in a floor are of 12m^2 similar to a 20 foot reefer. It came equipped with an ice battery bank of 6 kWh. This required a much higher temperature for the generation and bubble pumping thermal input however at nearly 190 Deg C.

A costing of the system for the larger 60 kW system required a larger capital outlay, nearly four times the capital outlay for a conventional system and the per unit annualized cost was approximately 15% higher considering a differential loan rate of 4% for solar absorption as opposed to 8% for conventional.

This when extrapolated to the Indian scenario however, can expect a significant drop in the installation and maintenance costs and the rising price of electricity(and the lack of it) would indeed minimize the gap on the 15% premium if not exceed it.

The 1 kW system was equal to the conventional system in terms of cost per kWh of cooling. As this is similar to the concept suited for containerized refrigeration, this is viewed with significant interest. The schematic of this system has been shown below:

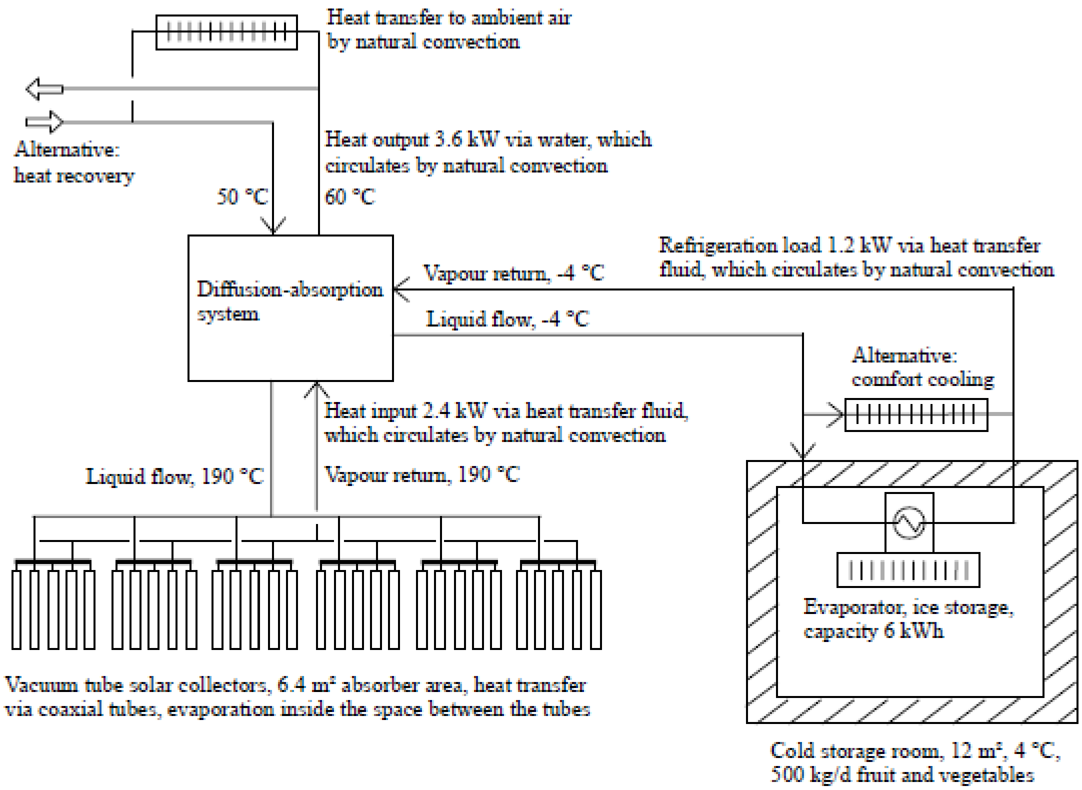

Figure 53, Diffusion Absorption Case Study Schematic, Source (Braun & Heb, pp.4,5)

The paper concluded that solar powered refrigeration for produce at this scale was indeed a feasible one based on real cases and its utility would be maximised where there was little electrical infrastructure and the cost of obtaining a connection and utilization would be prohibitive making it apt for off-grid applications.

Description of a possible system

The overall system is therefore envisaged to consist of small container fields at farm cluster aggregates in rural areas to reduce the median distance of transport. The aim being to optimize the overall weighted distance between farms, demand points and the container cluster. This would reduce both land requirements and land costs to what is required. As the system is modular, capacity may be increased gradually.

This would have associated solar collector fields producing solar thermal energy solely for refrigeration or producing both power and refrigeration based on waste heat. The choice would have to be determined by the requirement of the rural area and the number of bottom of the pyramid power consumers that can offset the costs of an electric generator and provide a revenue benefit that can be spread over the refrigeration system as otherwise the capital cost and payback periods may be extremely high to favour investment in the additional electricity generation system.

The container field would also have low cost phase change materials which would provide the energy storage for refrigeration for the hours when the sun is not shining.

The Customer Base

In a survey conducted by the National Survey Sample Organization (2006), it was identified that marginal land holdings of less than 1 hectare dominated the rural scene with nearly 70% (<1 hectare) of the survey samples allotted to this type of land holding. Just over 15% more was allotted to small holdings (1-2 hectares), nearly 10% to semi-medium holdings (2 to 4 hectares) and 4% to medium holdings (4-10 hectares). The area distribution was about 22% for each of the above categories with the remaining nearly 12% of land held by the 1% of large farm holdings.

The following is an excerpt from the 2011-2012 annual report from the department of agriculture depicting the sizes of land holdings and its proportional distribution (2012).

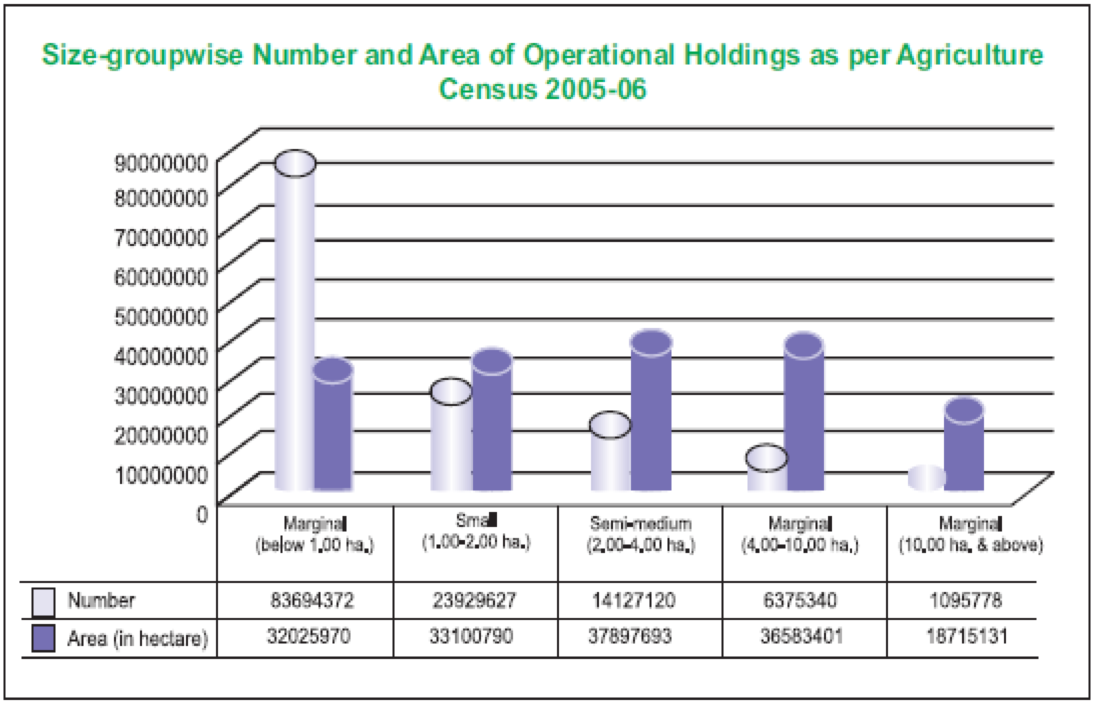

Figure 54: Area-wise Distribution of Land Holdings, Source (Department of Agriculture & Cooperation, Government of India, 2012, p.164)

With this structural break up of operational holdings, the major investors who would have both the ability as well as the motivation to fund these projects would be the organized retail sector followed by agricultural cooperatives representing marginal to small-medium farms, government funded initiatives, non-governmental organizations (NGO's). The medium to large farms would typically be on the priority listing for electrification.

Financial Support Measures

Solar Collection System

There exist capital subsidies on various solar collection systems in conjunction with refrigeration systems. A workshop on the present status on solar cooling by Dr. A. K. Singhal of the Ministry of New and Renewable Energy indicated the action plan to be 50% subsidy till 2015 for the cost of the solar system in non-profit making ventures and 35% in the event of profit making ventures (Singhal, 2009). The support is expected to be shifted to a savings based incentive scheme post 2015. The current indigenous production capability for concentrating solar power included 6 manufacturers of Scheffler dishes which was a specific design that was built and continuously modified to cater to the requirements of the environment of a developing nation using low cost materials.

The development goals stress the need to thrust the uptake of solar cooling systems for milk and fruits and vegetables. The investors in these systems, especially where solar power is being produced can recover costs through power production. Waste thermal heat of suitable grade can be used to run the refrigeration processes for the container systems as the absorption systems can run on lower input temperatures to the generator thereby increasing the systems efficiency. This would therefore have the potential to create a revenue stream through power as well which can be utilized by the bottom of the pyramid users. This in addition to the loan and tax subsidies on refrigeration systems conditions the market for favourable uptake of solar based cooling.

Refrigeration System

The recent budget has also allocated the entire cold chain investment with infrastructure status thereby reducing the loan rates on the entire chain. Import taxation reduction has also been introduced on equipment for cold chain infrastructure. 100% share in Foreign Direct Investment for the cold chain has also been announced to drive the cold chain (Das, 2012). This is expected to boost the investment in the cold chain. The investors in the refrigeration systems can be either agricultural cooperatives or organized retailers.

Refrigerated Space

With the containership model of refrigeration, organized retail where a seamless delivery chain exists can be used with the cost of the refrigerated space recoverable from the bottom of the pyramid users, i.e the farmers allowing the spread of the cost on a per usage basis.

6 Conclusions

An investigation into the refrigeration solutions for agriculture in India has been made using deductive reasoning based on evidence and case studies to arrive at the best possible approach for holistic development of the cold chain.

Heat driven refrigeration cycles were deemed most appropriate for the Indian scenario due to high solar insolation levels throughout the country.

Of the cycles, vapour absorption refrigeration systems were deemed ideal for the Indian rural scenario. The rationale behind this approach was suitably explored. This option is strengthened further due to the capacity to use waste heat from solar power production or ample bio mass and farm waste to run the thermal requirements even in the absence of sunlight.

Solar refrigeration systems for produce with ice battery banks were deemed a feasible option in India due to comparable design for insolation and ambient temperature conditions being established in the case studies.

Diffusion absorption systems would further reduce the need for parasitic pumping load experienced by vapour absorption system. Systems running on diffusion absorption cycles to cater to 1.2 kW refrigeration load with ice battery bank backup of 6 hours have been demonstrated with the resulting annualized cost at parity with conventional vapour compression systems.

The modelling of the small to middle scale cold storage converged on a containerized design to allow for suitable refrigerated transport. This would allow for easy transport cold chain link and readily cater to the development of the transport link which is weak at present.

The vapour absorption system also has the advantage of using transport exhaust gas heat in trucks to drive the absorption mechanism for refrigeration at levels found extremely satisfactory as per actual studies conducted with hydronic heat exchangers. This would modularize the cold chain while reducing refrigeration loading normally required by conventional systems during refrigerated transport of produce.

Even if the normal vapour absorption dual pressure cycle is considered, the small to middle scale option for storage would allow the spread of the cost of auxiliary systems for parasitic pump losses and cooling circulation loop losses to have a greater spread (if normal absorption cycle without bubble pumps is considered). This could be achieved through PV systems and minimal battery usage at cost effective levels.

In essence, modularization to container scales would allow the entire section of conventional cold storage surface fixed facility to be eliminated. This would allow the better capacity utilization as well as lower real estate costs where only solar collectors would be the permanent fixtures.

Areas to investigate further:

While vapour absorption machines are feasible for inland transport of produce on trucks using hydronic heat exchange, applications where sea freight is required will need an independent assessment on whether this method of containership transport is feasible as ships have very specific power production capacities and integration technologies for reefers requiring electrical input.

Further investigation would however be required if diffusion absorption systems are to be used to establish performance and suitability for transport purpose. The toxic nature of refrigeration systems containing ammonia and the non-availability and explosive nature of hydrogen would mean a shift from Platen-Munters cycle to Einstein’s refrigeration where different combinations of harmless refrigerants and associated absorbents and inert mixtures can be used.

7 Bibliography

Adhikari, A., 2008. Out of cold storage. *Business Today*, 1 June. Available Online: http://m.businesstoday.in/story/out-of-cold-storage/1/2178.html.

Alam, A.M., 2006. Agri-Exports : Challenges and Prospects. *CAB Calling*, October-December. p.54. Available at: http://www.cab.org.in/CAB%20Calling%20Content/Organic%20Agriculture%20and%20Food%20Industry%20-%20Trends,%20Challenges%20and%20Opportunities%20II/Agri%20Export%20-%20Challenges%20and%20Prospects.pdf [Accessed 22 August 2012].

Almén, C.G., n.d. *Platen-Munters Cycle*. [Online] Available at: http://www.absreftec.com/downloads/chapter01.pdf [Accessed 15 August 2012].

Alternative Energy Primer, n.d. *Linear Solar Concentrators*. [Online] Available at: http://www.alternativeenergyprimer.com/Linear-Solar-Concentrators.html [Accessed 30 July 2012].

Anyanwu, E.E., 2004. Review of solid adsorption solar refrigeration: An overview of the principles and theory. *Energy Conversion and Management*, 45, pp.1279-95. Available at - http://www.sciencedirect.com/science/article/pii/S0196890403002115.

Association for Social and Economic Transformation, n.d. *Estimation Loss of Horticulture Produce due to Non-availability of Post Harvest & Food Processing Facilities in Bihar & UP*. Study. Planning Commission, Government of India.

Bahaj, D.A.S., 1998. World's First Solar Powered Transport Refrigeration System. *Renewable Energy*, (15), pp.572-76. Available at - http://www.sciencedirect.com/science/article/pii/S0960148198002274.

Bahaj, A.S., 2000. Photovoltaic power for refrigeration of transported perishable goods. In *Photovoltaic Specialists Conference, 2000. Conference Record of the Twenty-Eighth IEEE*. Anchorage, AK, 2000. IEEE. Available at - http://ieeexplore.ieee.org//xpl/articleDetails.jsp?arnumber=916195.

Bahaj, A.S. & James, P.A.B., 2002. Economics of Solar Powered Refrigeration Transport Applications. In *Photovoltaic Specialists Conference, 2002. Conference Record of the Twenty-Ninth IEEE*., 2002. Available at - http://ieeexplore.ieee.org//xpl/articleDetails.jsp?tp=&arnumber=1190911&url=http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1190911.

Braun, R. & Heb, R., n.d. *Solar Cooling*. Paper. University of Applied Sciences Gelsenkirchen. Available at - http://www.wipage.de/solartransfer/download/downloads/braunpaper.pdf.

Cengel, Y.A. & Boles, M.A., 2006. *Thermodynamics : An Engineering Approach*. 5th ed. Tata McGraw-Hill.

Central Statistics Office, Government of India, 2012. *Energy Statistics*. Annual Government Report. National Statistical Organisation, Ministry of Statistics and Programme Implementation, Government of India. Available at - http://mospi.nic.in/mospi_new/upload/Energy_Statistics_2012_28mar.pdf.

Chakravarthy, V.S., Shah, R.K. & Venkatarathnam, G., 2011. A Review of RefrigerationMethods in the TemperatureRange 4–300 K. *Journal of Thermal Science and Engineering Applications*, 3(June).

Das, R., 2012. *Twelfth Five Year Plan in India (2012-2017): Instruments and Approach*. Policy Research Institute, Ministry of Finance, Japan. Avialable at - http://www.mof.go.jp/pri/research/conference/zk094/zk094_05.pdf.

Department of Agriculture & Cooperation, Government of India, 2012. *Annual Report 2011-2012*. Annual Governmental Report. Government of India. Available at - http://agricoop.nic.in/Annual%20report2011-12/ARE.pdf.

Desai, A., October 2011. *Case Study on Potential for Scaling Up: "Waste to Wealth by Incubating Mini Cold Storage Technology Ventures" in India*. The Heller School for Social Policy & Management, Brandeis University.

DMI, Ministry of Agriculture, Government of India, 2009. *Sector-wise Distribution of Cold Storages as on 31.12.2009*. [Online] Available at: http://agmarknet.nic.in/sectorwisecold2009.htm [Accessed 4 September 2012].

Economic Times Bureau, 2012. Innovation in cold chains and warehousing can make the country a leading exporter of horticulture products. *The Economic Times*, 2 February. Article by: Raghu Dayal Available at - http://articles.economictimes.indiatimes.com/2012-02-02/news/31017156_1_vegetables-fruit-export-share.

Economic Times, 2011. *Godrej to take Chotukool fridge to more markets this year*. [Online] Available at: http://articles.economictimes.indiatimes.com/2011-05-22/news/29571277_1_rural-markets-godrej-appliances-infrastructure [Accessed 02 September 2012].

Erickson, C., 2009. Rural milk preservation with the ISAAC solar icemaker. *Energy for Sustainable Development*, (13), p.287–291. Available at - http://www.sciencedirect.com/science/article/pii/S0973082609000763.

Federation of Indian Chambers of Commerce and Industry (FICCI), 2010. *Bottlenecks in Indian Food Processing Industry*. Survey Report. FICCI. Available at - http://www.ficci.com/SEDocument/20073/Food-Processing-Bottlenecks-study.pdf.

FnB News Bureau, 2011. *F&B News*. [Online] Available at: http://www.fnbnews.com/article/detnews.asp?articleid=30493&sectionid=32 [Accessed 3 September 2012].

Garrabrant, M.A., 1999. *Final Report: Waste-Heat Driven Absorption Transport Refrigerator*. [Online] Available at: http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/1236/report/F [Accessed 8 August 2012].

Anon., 2010. Growth Drivers and Challenges for Organised Retailing in India. In Gopal, V.V. & Suryanarayana, D.A., eds. *International Conference on Business and Economics Research*. Kuala Lampur, Malaysia, 2010. IACSIT Press. Available at - http://www.ipedr.com/vol1/6-B00008.pdf.

Gopal, V.V. & Suryanarayana, D.A., 2011. Growth Drivers and Challenges for Organised Retailing in India. *2010 International Conference on Business and Economics (ICBER)*, 1, p.27. Available at: http://www.ipedr.com/vol1/6-B00008.pdf [Accessed 23 August 2012].

Goswami, R., n.d. *Industrialising India's Food Flows: An analysis of the food waste argument*. Paper. Available at - http://www.macroscan.com/anl/may11/pdf/Food_Flows.pdf.

Government of India, 2012-13. *Union Budget, Government of India*. http://indiabudget.nic.in.

Green Rhino Energy, 2012. *Solar Power*. [Online] Available at: http://www.greenrhinoenergy.com/solar/radiation/spectra.php [Accessed 24 July 2012].

Haque, D.T., n.d. *Improving the Rural Poors' Access to Land in India*. Council for Social Development. Available at - http://indiagovernance.gov.in/files/improving-rural-poor-access-to-land-t-haque.pdf.

HORUZ, I., 1998. An Alternative Road Transport Refrigeration. *Tr. J. of Engineering and Environmental Science*, (22), pp.211-22. Available at - http://journals.tubitak.gov.tr/engineering/issues/muh-98-22-3/muh-22-3-7-97005.pdf.

InvenSor, 2012. *InvenSor - Adsorption Technology*. [Online] Available at: http://www.invensor.com/en/technology/adsorption-technology.htm [Accessed 1 September 2012].

Jairath, M.S., n.d. Agricultural Marketing Infrastructural Facilities in India - State Wise Analysis. Available at - http://www.cosamb.org/downloads/Dr%20Jairath%20%5b1%5d.MSJ_PPT.ppt.

Jairath, M.S., post 2010. *COSAMB Downloads*. [Online] Available at: www.cosamb.org/downloads/MISINDIA-Cosamb(F).doc [Accessed 04 September 2012]. M.S. Jairath is the director of the National Institute of Agricultural Marketing.

Joshi, R., Banwet, D. & Shankar, R., 2009. Emerald Article: Indian cold chain: modeling the inhibitors. *British Food Journal*, 111(11), pp.1260 - 1283.

Kalogirou, S., 1998. Use of parabolic trough solar energy collectors for sea-water desalination. *Applied Energy*, 60, pp.65-88. Available at - http://www.sciencedirect.com/science/article/pii/S030626199800018X.

Kalogirou, S.A., 2004. Solar thermal collectors and applications. *Progress in Energy and Combustion Science*, pp.231-95. Available at - http://www.sciencedirect.com/science/article/pii/S0360128504000103.

Kapoor, P., Adhikari, T. & Saraiya, A., 2012. *Sprouting Opportunities in Food & Agriculture Sector*. technopak. http://www.technopak.com/Images/F&A%20Outlook.pdf.

Kim, D.S. & Ferreira, C.A., 2008. Solar refrigeration options – a state-of-the-art review. *International Journal of Refrigeration*, (31), pp.3-15. Available at - http://www.sciencedirect.com/science/article/pii/S0140700707001478.

Kopp, G. & Lean, J.L., 2011. A new, lower value of total solar irradiance: Evidence and climate significance. *GEOPHYSICAL RESEARCH LETTERS*, 38. Available at - http://www.atmosp.physics.utoronto.ca/~jclub/journalclub_files/kopp_lean_2011.pdf.

KPMG IN INDIA, 2009. *Food processing and Agri business*. http://www.kpmg.de/docs/Food_Processing_and_Agribusiness.pdf.

KPMG IN INDIA, 2009. *Infrastructure Development in Agriculture*. Advisory Report. New Delhi. Available at - https://www.kpmg.com/IN/en/IssuesAndInsights/ArticlesPublications/Documents/Infrastructure%20Development%20in%20Agriculture%20-%20Route%20to%20Rural%20Transformation.pdf.

KPMG, 2011. Food Retail & Supply chain and Agro logistics. In *Supply Chain Leadership Council, Summit & Awards 2011*., 2011. http://www.scic.in/pdf/food-retail-presentation/KPMG.pdf.

Kumar, A., 2012. *Solar-Biomass Hybrid Cold Storage-cum-Power Generation system for Rural Applications*. [Online] Available at: http://www.teriin.org/index.php?option=com_featurearticle&task=details&sid=745 [Accessed 4 July 2012].

Li, M., Sun, C.J., Wang, R.Z. & Cai, W.D., 2004. Development of no valve solar ice maker. *Applied Thermal Engineering*, (24), pp.865-72. Available at - http://www.sciencedirect.com/science/article/pii/S1359431103003119.

Maheshwar, C. & Chanakwa, T.S., 2006. POSTHARVEST LOSSES DUE TO GAPS IN COLD CHAIN IN INDIA-A SOLUTION. In *ISHS Acta Horticulturae 712: IV International Conference on Managing Quality in*

Chains - The Integrated View on Fruits and Vegetables Quality., 2006. Available at - http://www.actahort.org/books/712/712_100.htm.

Maheshwar, C., n.d. Solar Power for Post Harvest Losses - A Sensible Solution for Developing Countries. In *World Energy Congress*. World Energy Council. Available at - http://www.worldenergy.org/documents/congresspapers/160.pdf.

Ministry of Agriculture, Govenrment of India, 2009. *Cold Storage, India*. [Online] Available at: http://agmarknet.nic.in/coldstorage.htm [Accessed 02 September 2012].

Ministry of Finance, Government of India, 2011-12. *Economic Survey 2011-12*. [Online] Available at: http://indiabudget.nic.in/es2011-12/echap-08.pdf [Accessed 20 August 2012].

MoFPI, Government of India, 2010. Cold chains adding zing to Indian FPI. *Food Processing Alert*, August. Available at: http://www.indianconsulate.org.cn/userfiles/file/Copy%20of%20Newsletter%205_final%20for%20email.pdf [Accessed 22 August 2012].

MoFPI, 11th Plan of India. *Strategic Plan: MoFPI*. Governmental Strategic Plan. Ministry of Food Processing Industries, Government of India. Available at - http://mofpi.nic.in/images/File/finalstrategyplan.pdf.

MoFPI, 2007. *Ministry of Food Processing India - Opportunities in the food sector*. [Online] Available at: http://mofpi.nic.in/ContentPage.aspx?CategoryId=199 [Accessed 3 August 2012].

Monsef, H., Zadegan, N. & Javaherdeh, K., 2012. *Design and Construction of a Low Capacity Pump-Less Absorption System*. Original Scientific Paper. Iran: University of Guilan. DOI - 10.2298/TSCI120119016M - Available at - http://www.doiserbia.nb.rs/img/doi/0354-9836/2012%20OnLine-First/0354-98361200016M.pdf.

Moreno-Quintanar, G., Rivera, W. & Best, R., 2011. Development of a solar intermittent refrigeration system for ice production. In *Solar Thermal Applications*. Linkoping, Sweden, 2011. World Renewable Energy Congress 2011 - Sweden. Available at - http://www.ep.liu.se/ecp/057/vol14/048/ecp57vol14_048.pdf.

Munuswamy, S., 2009. *ChotuKool: the $69 fridge for rural India*. [Online] Available at: http://www.gizmag.com/refridgerator-rural-india-chotukool/13680/ [Accessed 02 September 2012].

NABARD, 2011. *Organised Agri-Food Retailing in India*. Mumbai: National Bank for Agriculture and Rural Development. http://www.nabard.org/fileupload/DataBank/Publications/Nabard%20E%20Book.pdf.

National Horticulture Board, 2011. *National Horticulture Database 2010*. Database. Aristo Printing Press. Available at - http://www.nhb.gov.in.

National Sample Survey Organization, 2006. *Report on Household Ownership Holdings in India*. Government of India.

NewsDesk, 2012. Cold Chains: The Essential Infrastructure. *Logistics Week*, April. Report by - Purvin Patel ; Available at - http://logisticsweek.com/infrastructure/2012/04/cold-chains-the-essential-infrastructure/.

Nixon, J.D., Dey, P.K. & Davies, P., 2010. Which is the best solar thermal collection technology for electricity generation in north-west India? Evaluation of options using the analytical hierarchy process. *Energy*, (35), pp.5230-40. Available at - http://www.sciencedirect.com/science/article/pii/S0360544210004172.

Norton, B., 2011. *Solar Energy*. [Online] Available at: http://www.thermopedia.com/content/1136/ [Accessed 2 July 2012]. DOI:10.1615/AtoZ.s.solar_energy.

Patil, A.V. & Kholkumbe, B.S., 2010. A Study of Contemporary Agricultural Export Marketing System in India. In *Eighth AIMS International Conference on Management*., 2010. Available at - http://icmis.net/AIMS8%20to%20print/P%208818-proofs%20.pdf.

POSHARP, 2012. *Photovoltaic Panel Efficiency and Performance*. [Online] Available at: http://www.posharp.com/photovoltaic/panelefficiency/database.aspx [Accessed 30 July 2012].

Power and Energy Division, Government of India, 2011. *Annual Report 2011-2012 on the working of State Power Utilities & Electricity Departments*. Annual Government Report. Power & Energy Division, Planning Commission, Government of India. Available at - http://planningcommission.nic.in/reports/genrep/arep_seb11_12.pdf.

Pridasawas, W., 2006. *Solar-Driven Refrigeration Systems with Focus on the Ejector Cycle*. PhD Thesis. Stockholm: Royal Institute of Technology, KTH: School of Industrial Engineering and Management.

PRINCE, n.d. *Parabolic Dish Cooker*. [Online] Available at: http://www.princeindia.org/newproducts.htm [Accessed 22 August 2012].

Quaschning, V., 2003. *Solar thermal power plants*. [Online] Available at: http://www.volker-quaschning.de [Accessed 22 August 2012]. Published in Renewable Energy World 06 (2003) pp 109 -113.

Ramachandran, T.V., Jain, R. & Krishnadas, G., 2011. Hotspots of solar potential in India. *Renewable and Sustainable Energy Reviews*, (15), pp.3178-86. Available at - http://www.sciencedirect.com/science/article/pii/S1364032111001444.

Selvakumar, N. & Barshilia, H.C., 2012. Review of physical vapor deposited (PVD) spectrally selective coatings for mid and high-temperature solarthermal applications. *Solar Energy Materials & Solar Cells*, (98), pp.1-23. Available at - http://www.sciencedirect.com/science/article/pii/S0927024811005939.

Sharma, V.P. & Jain, D., 2011. *High-Value Agriculture in India: Past Trends and Future Prospects*. Working Paper. Indian Institute of Management, Ahemdabad (IIM A). Available at - http://www.iimahd.ernet.in/assets/snippets/workingpaperpdf/2144213256 2011-07-02.pdf.

Short, D.N.M., n.d. *METEOROLOGY - WEATHER AND CLIMATE: A CONDENSED PRIMER*. [Online] Available at: http://www.fas.org/irp/imint/docs/rst/Sect14/Sect14_1a.html [Accessed 04 September 2012].

Singhal, D.A.K., 2009. *Present Status & Action Plan on Solar Cooling*. Workshop on Solar Cooling. Ministry of New & Renewable Energy, Government of India. Available at - http://www.aprekh.org/files/A_K_Singhal.pdf.

Spakovszky, Z.S., Waitz, I.A. & Greitzer, E.M., n.d. *Concept and Statements of the Second Law*. [Online] Available at: http://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node37.html [Accessed 24 August 2012].

SunDazer, n.d. *SunDazer Solar Refrigerated Containers*. [Online] Available at: http://www.sundanzer.com/documents/SolarContainers.pdf [Accessed 22 July 2012].

technopak, 2010. *Perspective, Volume 3*. http://www.technopak.com/Images/TPK-perspective-vol3.pdf.

The Energy and Resources Institute, 2011. *Solar Biomass Hybrid Cold Storage-cum Power Generation System*. [Online] Available at: http://www.teriin.org/index.php?option=com_ongoing&task=about_project&pcode=2009RT01 [Accessed 7 July 2012].

Thevenard, D. & Haddad, K., 2006. Ground reflectivity in the context of building energy simulation. *Energy and Buildings*, 38, pp.972-80. Available at - http://www.sciencedirect.com/science/article/pii/S037877880500229X.

Tyagi, V.V., Kaushik, S.C. & Tyagi, S.K., 2012. Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology. *Renewable and Sustainable Energy Reviews*, (16), p.1383– 1398. Available at - http://www.sciencedirect.com/science/article/pii/S1364032111006058.

White, S.J., 2001. *Bubble Pump Design and Performance*. MS thesis. Georgia Institue of Technology.

Working Group, Agricultural Division, Planning Commission, Government of India, 2011. *Report of the Working Group on Agricultural Marketing Infrastructure, Secondary Agriculture and Policy Required for Internal and External Trade for the XII Five Year Plan, 2012-2017*. Government Report. Government of India. Available at - http://planningcommission.nic.in/aboutus/committee/wrkgrp12/agri/weg_rep_market.pdf.