Chapter 5
Model Validation, MATLAB Simulation and Results

5.1 Introduction

The previous chapters have been dealt with hybrid models for the crude oil heating applications. In this chapter, all three research studies carried out have been validated using MATLAB simulation and results are discussed. Figure. 5.1 shows the sequence of Simulation and results.

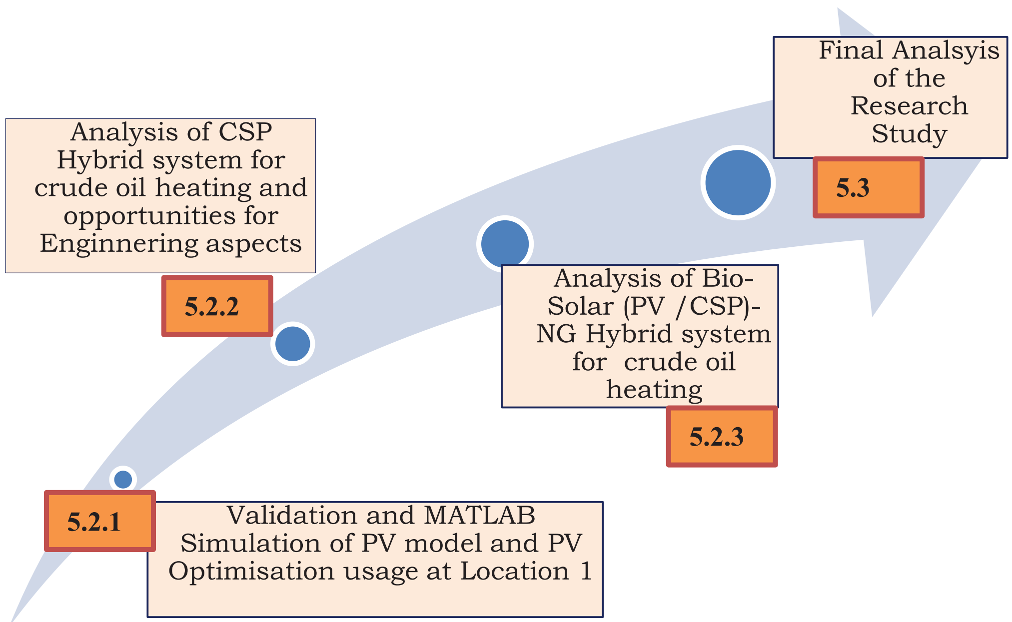


Figure. 5.1. Discussion, Simulation and Results for the work

The major focus of this chapter is on interdisciplinary research results on utilizing Solar power usage optimization at location1, hybrid system for crude oil heating and finally utilization of microalgae for carbon capture.

5.2 Solar PV optimization and Validation

The first focused research study is on 'decision making despatcher' system for solar power optimization at location 1. First step has been thought for the compatibility of PV power in conjunction with grid power [91]. The effective and efficient PV power and maximum power transfer to load, the Cuk converter has been selected for location and a SIMULINK model has been created taking Figure. 2.14 as compatible reference for location 1. The design parameters have been mentioned in Table 5.1 for Cuk converter circuit shown in Figure. 2.9 [51]

5.2.1. Design of CUK Converter

Utilizing the state space equations, the design of Cuk converter has been modeled to minimize output voltage deviation to input voltage disturbances.

Table 5.1. Objective and design requirements of Cuk Converter

Input voltage V_g	43-76 V DC
Output voltage V_O	200 V DC
Output Power P_O	100W- 500 W
Switching frequency f_s	250kHz
Efficiency for all input voltage and output power conditions	>90%
Peak-peak value of output voltage ripple	< 10 V
Peak-peak value of current ripple on input inductor	L_1 < 20%, on L_2 < 50%

Continuous Conduction Mode (CCM) has been assumed for converter operating theme and maximum acceptable output voltage ripple as 5%. The solar PV array has V_{OC}= 86 V with two modules are in series. For Cuk Converter duty ratio D, the design parameters have been derived from Table 5.2.

Table 5.2. Cuk Converter design parameters formulae [51]

Parameters	Formulae	Storage Elements Values
Duty Cycle(D)	$\frac{V_{Out}}{V_{in}} = \frac{D}{(1-D)}$	L_{1min}= 130 µH, L_{2min}= 70 µH, C_{1min}= 20 µF, C_{2min}= 10 µF
Minimum value of L_1	$L_{1\,min} = \frac{(1-D)R}{2Df}$	
Minimum value of L_2	$L_{2\,min} = \frac{(1-D)R}{2f}$	
Coupling capacitor(C)	$C_{1\,min} = \frac{DV_{Out}}{V_{ref}Rf}$	
Filter Capacitor	$C_{2m=} \frac{(1-d)V_{Out}}{V_{ref}8L_{2min}f^2}$	

Five parameters SIMULINK model of PV system at location 1 has been created and simulated. The Scope of Simulink model as shown in Figure 5.2 (3 phase current and voltage) has been plotted in the Figure 5.3 and Figure 5.4 respectively.

5.2.2. MATLAB Simulation of PV modeling at Location 1

The MATLAB / SIMULINK model has been created and shown in Figure 5.2.

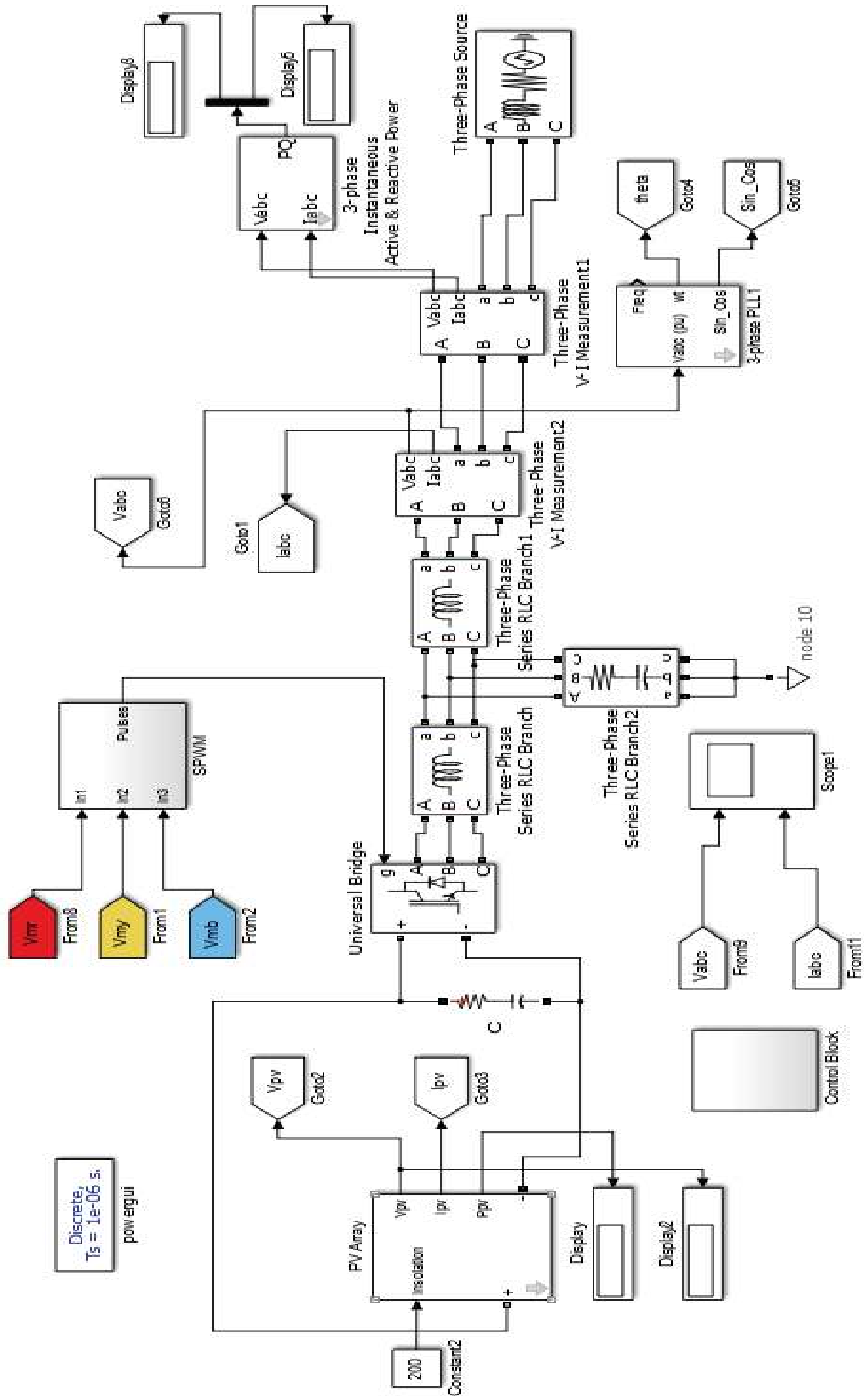


Figure. 5.2. SIMULINK model for real industrial site location 1

The simulations results are shown in Figure 5.3. and Figure 5.4

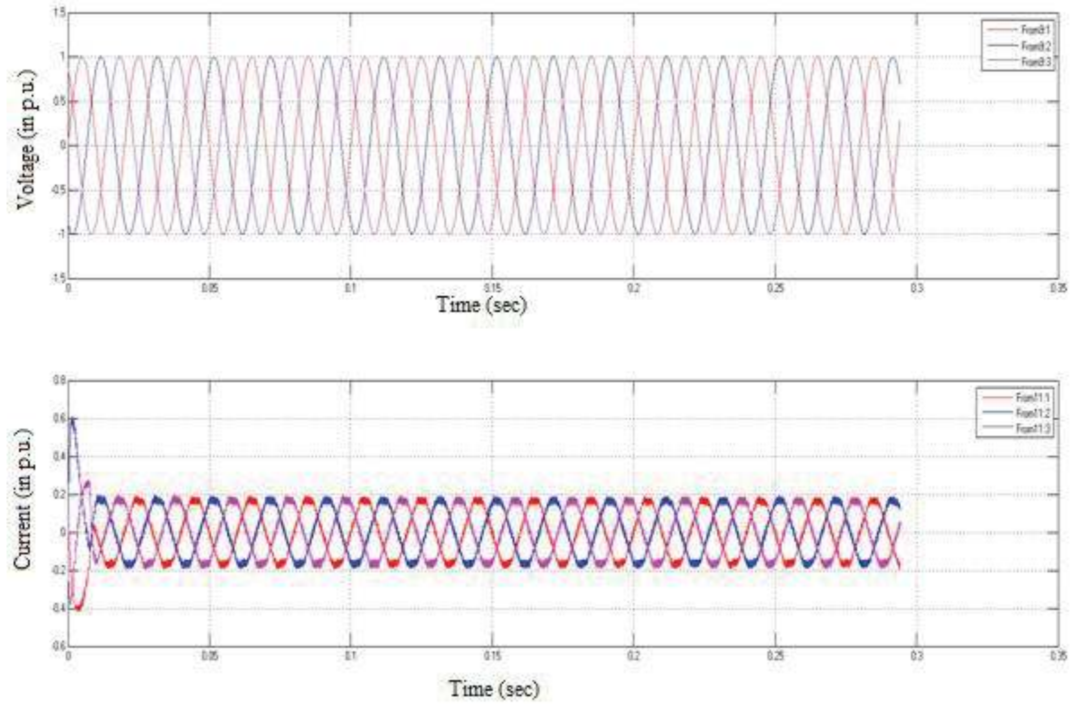


Figure. 5.3. 3 phase V-I charcaterstics of SIMULINK model during start

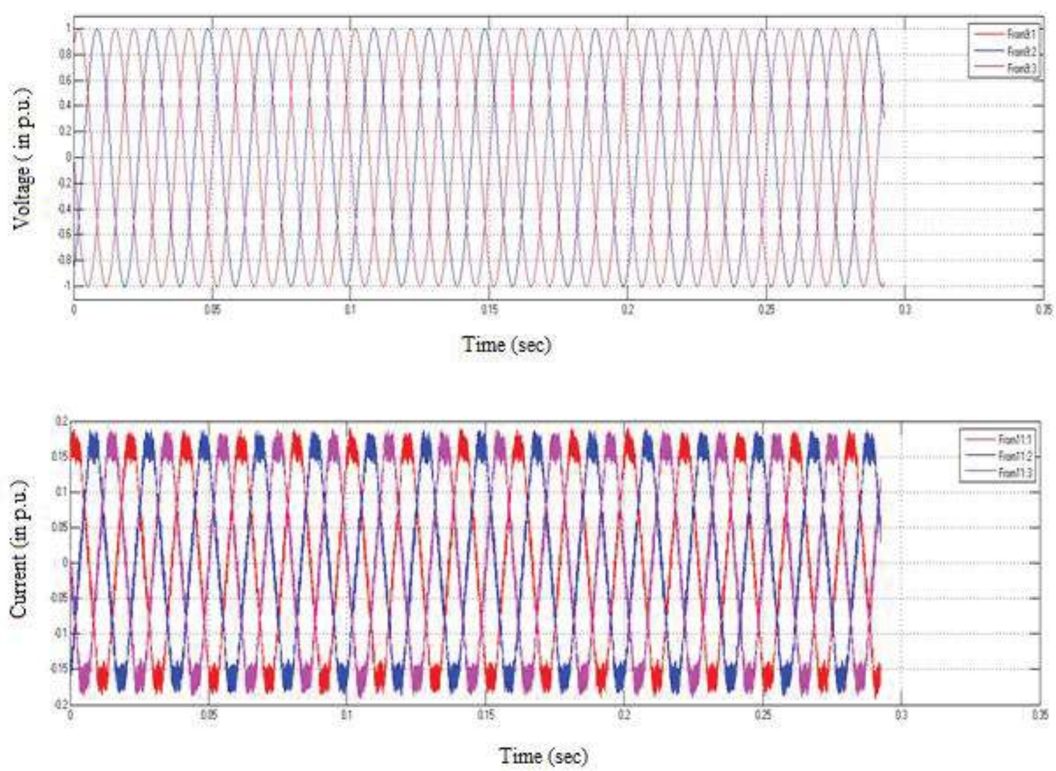


Figure. 5.4. Stabilising V-I charcterstics of the SIMULINK model

The Simulation results from Figure 5.3 and Figure 5.4 explain that Solar electricity has been found compatible to the existing grid electricity. Accordingly the solar PV model has been selected for its optimization at location 1.

5.2.3. Despatcher module description

As shown in Figure 3.3 of Chapter 3, the despatcher receives the data from diffident blocks and control energy consuming devices and estimates the amount of free solar energy. This estimation develops the strategy for ON/OFF of the devices based on their 'work times' as briefed in Table 5.3 and the step by step function of despatcher module has been explained in Table 5.4 [92].

Table 5.3. Parameters of devices from the First & Second group

Device	Power(Watts)	Work Cycle(Minutes)	Due time(hrs)
1st Group	100	60	14.5
2nd Group	Case 1		
	200	70	14.5
	Case 2		
	500	70	14.5

Table 5.4. Despatcher functional methodology for the First & Second group

Despatcher functional methodology	
Solar Power Generation Prognosis (Estimation of the solar power generation)	
Step 1	Calculation of solar beam irradiance components and sun positions using standard model described in Chapter 3. The model estimates the solar power generation using MATLAB code incorporating orientation of panel, cloud, rain and shading.
Estimation of uncontrolled consumption propagation	
Step 2	The uncontrolled consumption propagation does not depend on the external conditions, and so prognosis do not change with time. The simplest *Linear Moving Average (MA) model* has been mentioned in section 3.2.10 estimates the uncontrolled consumption for full power consumption cycle. Also the continuous monitoring of grid electricity consumption is recorded in the despatcher block.
Step 3	Data collection of step 1 and step 2 and estimation of the amount of available free solar energy. The free solar energy has been

	calculated as difference between the estimated solar power generation and uncontrolled consumption prognosis.
Step 4	Since weather parameters are varying, solar power prognosis also changes, the solar power propagation block must be executed not only once (in the beginning of the day), but repeatedly during the despatcher work at regular time period of 1 hour.
Step 5	Despatcher selects the devices from first group or second group based on their power (watts requirement), work cycle time and available free solar energy. Accordingly it provides the choice of the most convenient time to start and stop the device.
Step 6	The MATLAB implementation of the despatcher, the target value is chosen as the minimum value. During simulation a problem of instantaneous switching of device has been noticed and to solve this problem, another parameter called 'dead zone' value is also added which is actually a value around the target value.
Step 7	The despatcher block measures the power consumed each hour of the day by multiplying their work time in hours and the average energy price.
Step 8	Despatcher checks the work cycle length and device consumption power and compares estimated free power amount. The situation, when the consumption of the device is lesser that solar panel generation at any time of the day this device will start.
Step 9	The realization of time delays and external interruptions are used for the program time synchronization. Every hour, the despatcher gets the estimated solar panels generation and uncontrolled consumption data from the power and consumption modules.

As in Step 8 situation, when the consumption of the device has been bigger than solar panels generation at any time of the day is quite possible, so the possible time matrices need to be zero, as such this device will never start. Special climb down coefficient has been used for such time combination, which decreases fraction of device consumption [93].

Basically, it contains 'n' time programmed devices and each of them can have 'm' possible start times, and have numerous variants of its combinations. Resulting formula for despatcher for free energy from the solar panels consist of three elements: estimated generation, estimated uncontrolled consumption and consumption of started controllable time programmed devices. These inclusions have been included in the test realization of the Matlab® program time synchronization using hour and minute loops.

$$N = \prod_{i=1}^{n} m_i \tag{5.1}$$

Unfortunately, MATLAB does not support vectors of vectors, only matrices, so the number of variants must be:

$$N = m^n \tag{5.2}$$

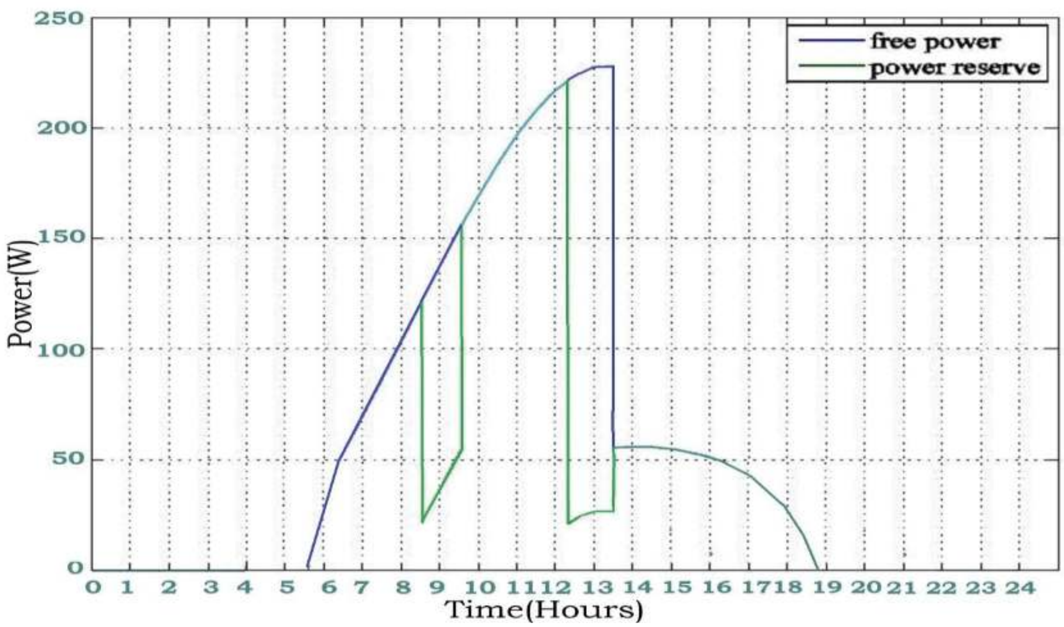


Figure. 5.5. Free power and power reserve estimated for the 19th June.

The power reserve has been computed as a minimum difference between the free power and total devices consumption. The Figure. 5.5 shows the situations when the system maximizes the minimum power reserve and the start of the largest consumer of 100 W has been postponed to the situation of the maximum of the solar power generation. The testing of despatcher MATLAB code shows that usage of solar power increases gradually and decreases the usage of grid electricity. Hence, the designed system reduces the total cost of electricity and increases the system effectiveness of solar panels.

To test the despatcher in condition of solar panels power deficit, best device start times combinations has been found for the devices with consumption bigger than in previous time. The results in Figure 5.5 and Figure 5.6 have been achieved for the constant electricity price and real electricity prices respectively.

The power reserve computed for the real electricity prices need to be compared with pool electricity prices of Indian electricity exchange price.

From Figure 5.6, it has been interpreted that the power production from the solar panels cannot cover the power consumption of the second device, so there is no power reserve and the system has to use electricity from the grid. In such condition, the composed function computes the price of the electricity consumed from the grid and this price must be minimized, from the Figure 5.6. Accordingly, the system place the start time of the second device at 11:35 and this device consumes electricity from the grid from 11:35 till 12:45 hrs. In such situation, the excesses of generated power returned to the grid before the start and after the end of the device work will compensate a part of energy taken from the grid during the device work, and hence, decrease the total electricity price.

All this routine of dispatching devices programmed by time and sensor values has been repeated every minute. Every hour system will re-estimate the solar power generation and uncontrolled consumption recalculate the amount of free power. After the estimation of the devices the start times optimal for new power estimation it will start dispatching devices again.

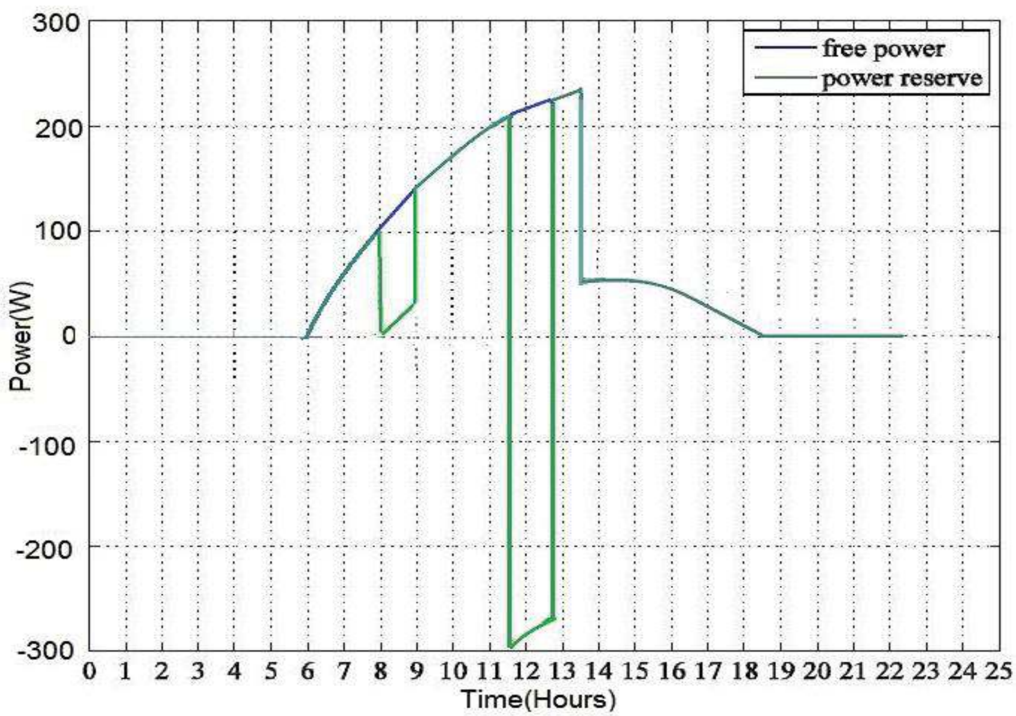


Figure. 5.6. Solar deficit: Power reserve for the 19th June

The functioning of despatcher has been tested and measurements of power consumption and solar panels power generation were recorded for the selected day of 19th June 2017, when weather was mainly cloudy, without glades and was changing during day long. The graph of grid power consumption changing during the 19th June 2017 has been shown in Figure. 5.7.

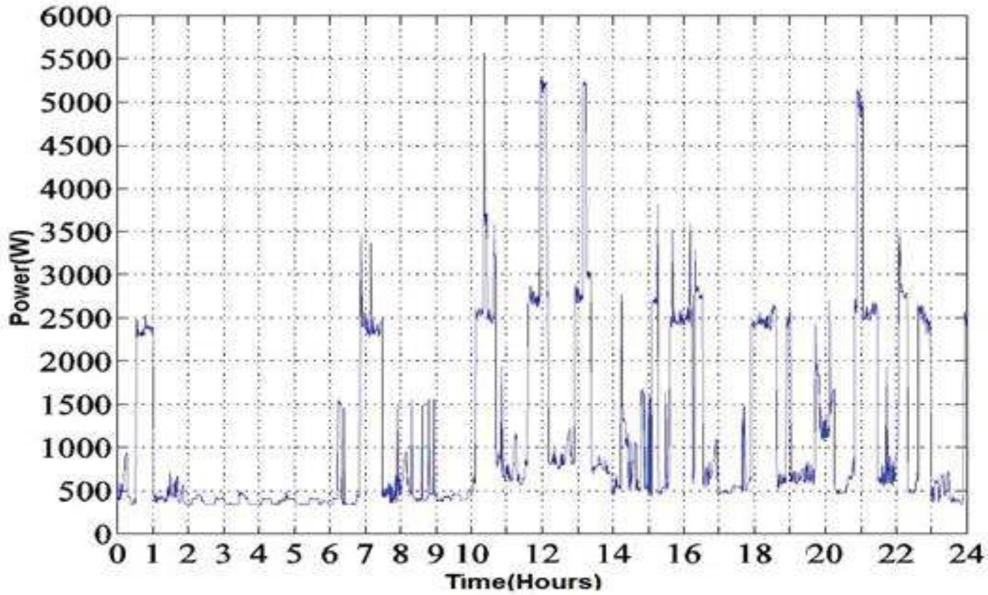


Figure. 5.7. Power consumption at plant during the 19th June

Figure 5.7 reflects the consumption of devices, such as instrument air compressors and booster compressors. Spikes correspond to equipment which have been running at intervals and consuming high power at some moments.

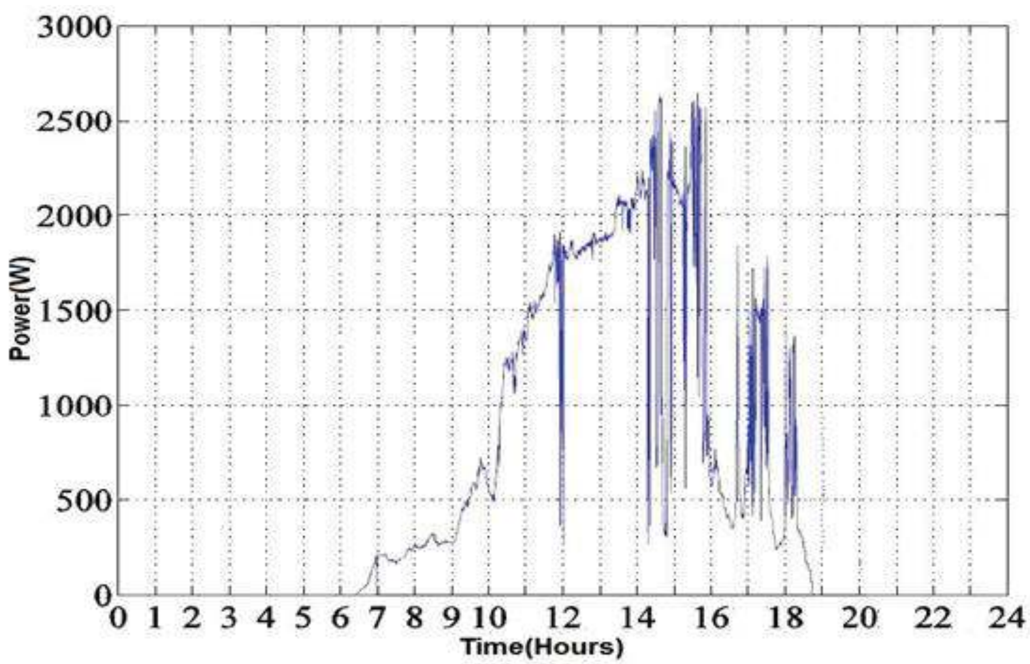


Figure. 5.8. Solar panels power generation during the 19th June

The profile of solar power generation during the 19th June 2017 has been shown in Figure 5.8 and it has been observed that solar power generated has been returning to the grid power which is basically free, but not being utilised. The Solar power returning to the grid has been also recorded and presented in Figure 5.9 and it was estimated that 4.246 kW free solar power has been lost.

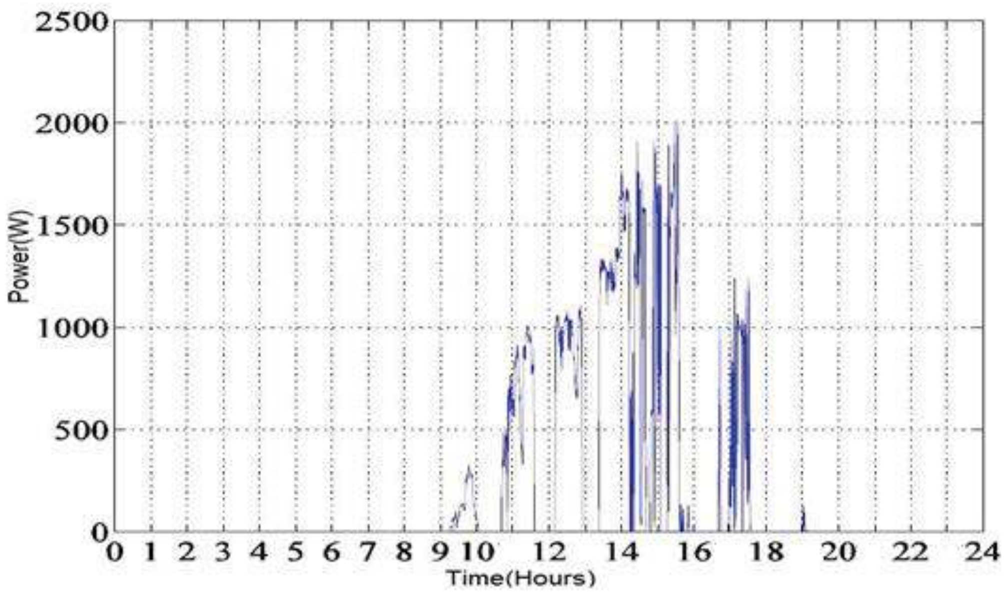


Figure. 5.9. Solar panels generated power returned to the grid

The despatcher based control system described in this work has been conceptualised to change such situations of lost solar energy and it has been tested for the optimization of energy consumption. The model has been tested for the energy consumption by two major devices in the plant as compared in Table 5.5

Table 5.5. Device parameters for six parameters

Value	**Devices**					
	1st	2nd	3rd	4th	5th	6th
Power(Watts)	1700	1700	1700	1700	1700	1700
Work Cycles (minutes)	60	60	60	60	60	60
Due time(hours)	11	12.5	14	16.5	19	24

Long periods of energy consumption refer to the devices from group 2, where the work time is much shorter than to group 1 device. Average work period of the group 1 device is 1 hour and average consumption is 1700 Wh. The energy consumption by selected both group device has been shown in Figure 5.10.

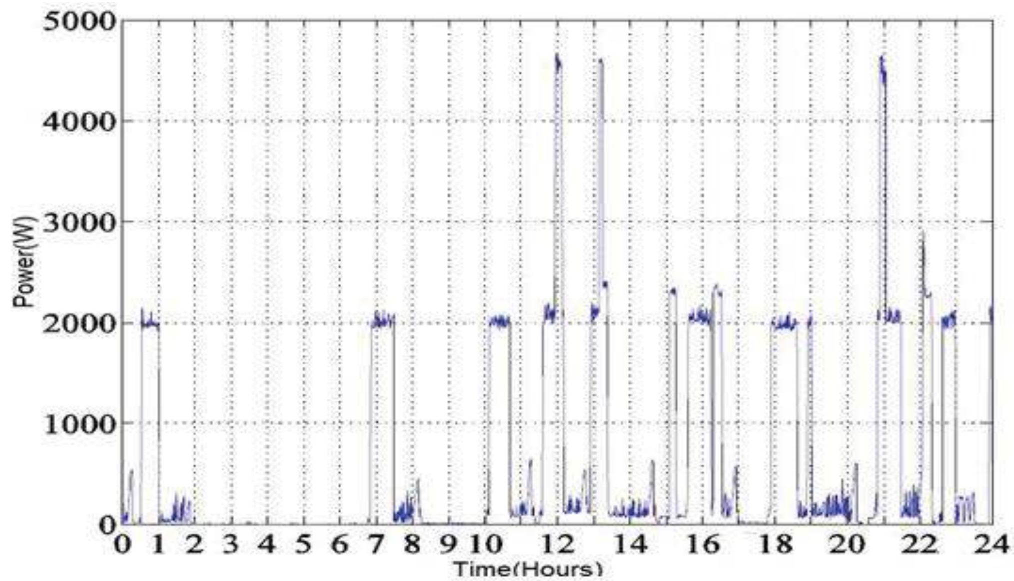


Figure. 5.10. Energy consumption by selected both group devices

The MATLAB programme was tested to start 6 both group devices with parameters described in Table 5.5 and the control system has chosen such start times for devices: 10, 11, 12, 13, 14, 15 o'clock. This is to test how accurate the control system could optimize the energy consumption for group 1 and group 2 devices. System will define time when this device can be started and when it will be prepared to start. Resulting power simulation comparison has been shown in Figure 5.11.

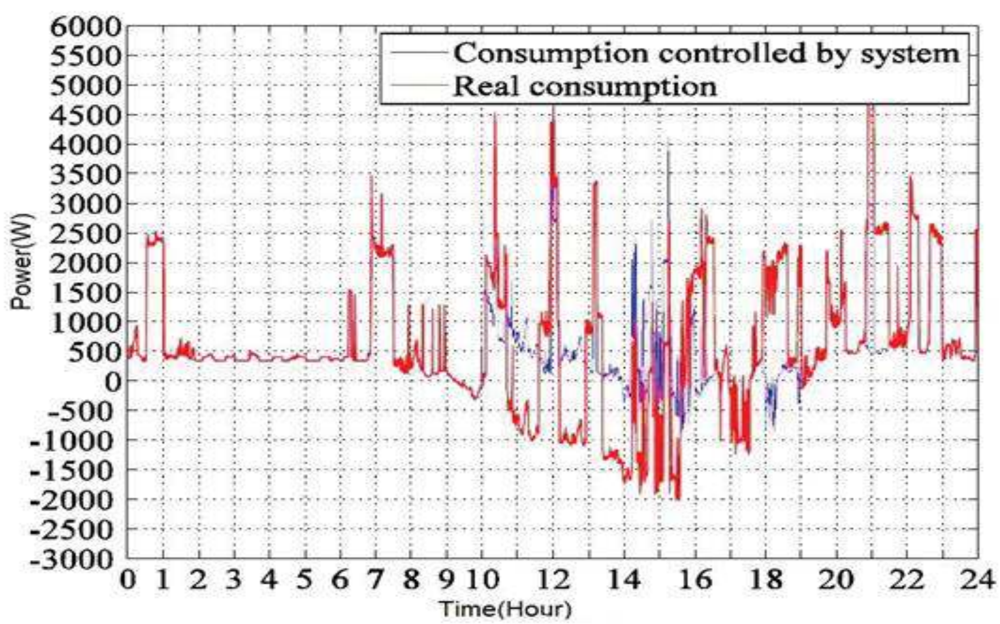


Figure. 5.11. Comparative consumption control with designed despatcher

The designed system consumption from the grid has been found 15.209 kWh, and only 0.958 kWh of solar panels generated electricity is returned to the grid. In-house usage of solar generated electricity rose from 8.939 kWh to 12.227 kWh. Hence it could summarised that by utilising the solar generated electricity (which otherwise would have lost), the efficiency of generated electricity has risen 37% higher due to despatcher programmed control system. It has been also observed that during the same period grid power consumption decreases, which further improves the cost efficiency of the system.

Test of control system shows that the efficiency of solar power usage has been increased by 34% and the use grid power decrease by 18%. It could be stated then, the control system improves main initial aim of increase efficiency of solar power usage and decrease total grid energy cost. Negative consumption on Figure 5.11 suggests that the solar power generated has been feeding to grid supply.

5.3 Crude Oil Heating applications utilizing CSP Technology

The prototype CSP dish has been developed, tested and demonstrated. The performance of solar concentrator has been found dependent upon solar radiation insolation, site condition, sunshine hours and other parameters.

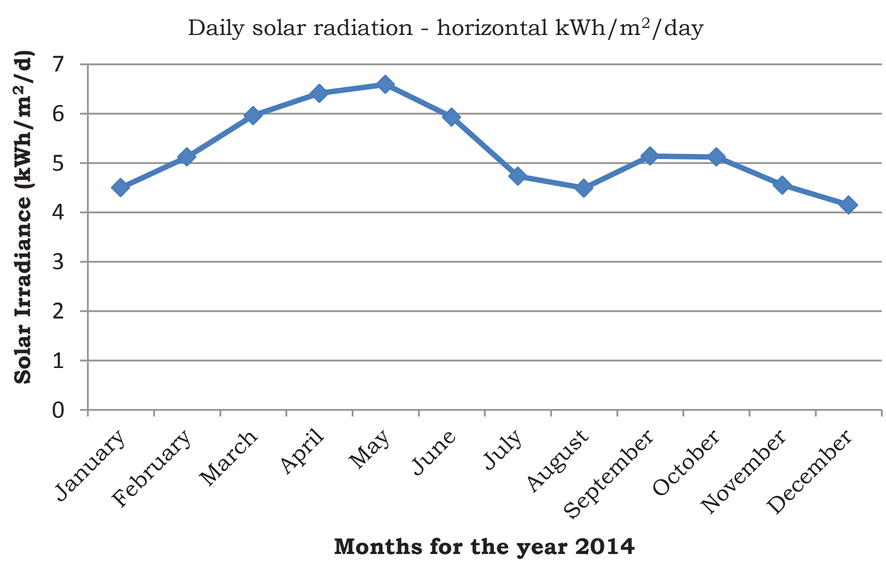


Figure. 5.12. Solar beam radiation at location 2

The concentrated thermal energy generated by a CSP system has been utilized by heater treater system for the heat exchanging process. The crude oil temperature seen varying and finally settled down to the required settings of

80°C, this fluctuations in temperature has effected the crude oil production, but within the limits and maintained by site operational team.

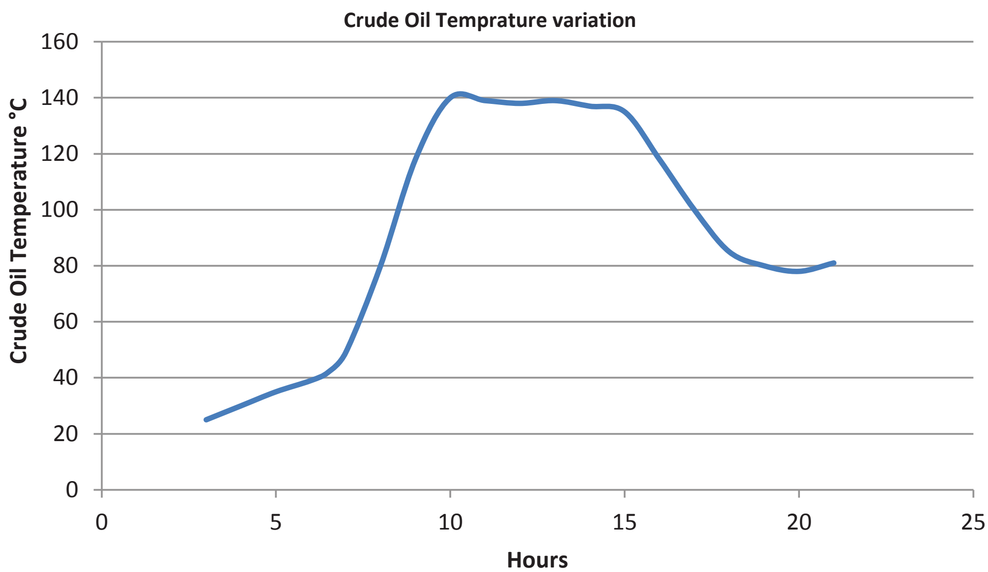


Figure. 5.13. Crude oil temperature variation with CSP system

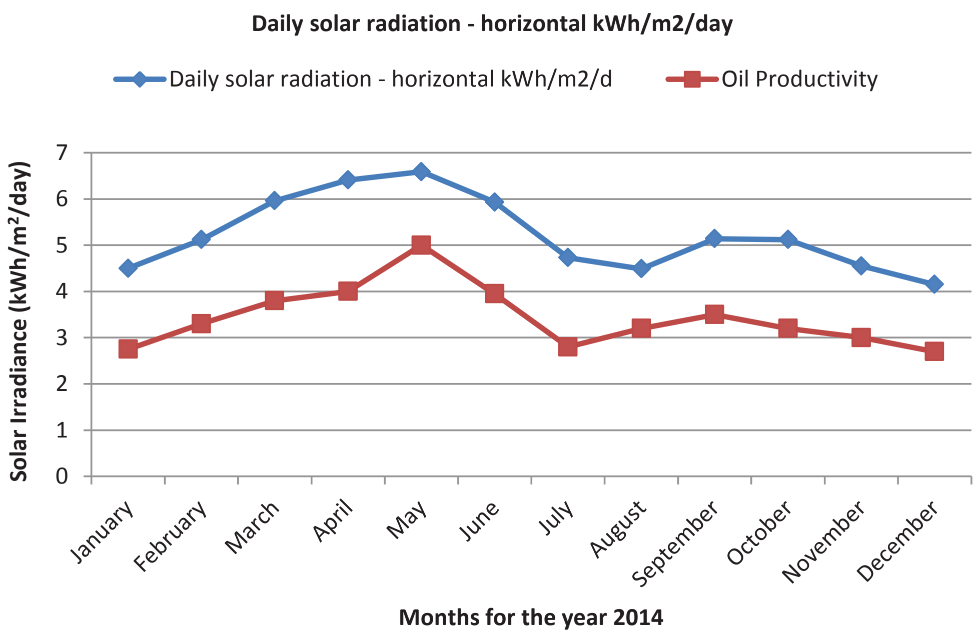


Figure. 5.14. Effect of crude oil production with solar irradiation.

The thermal storage systems could have given the better results and reliability during the cloudy and night-time conditions. It has been seen that instantaneous power was required to meet expected and unexpected peak demand during the process.

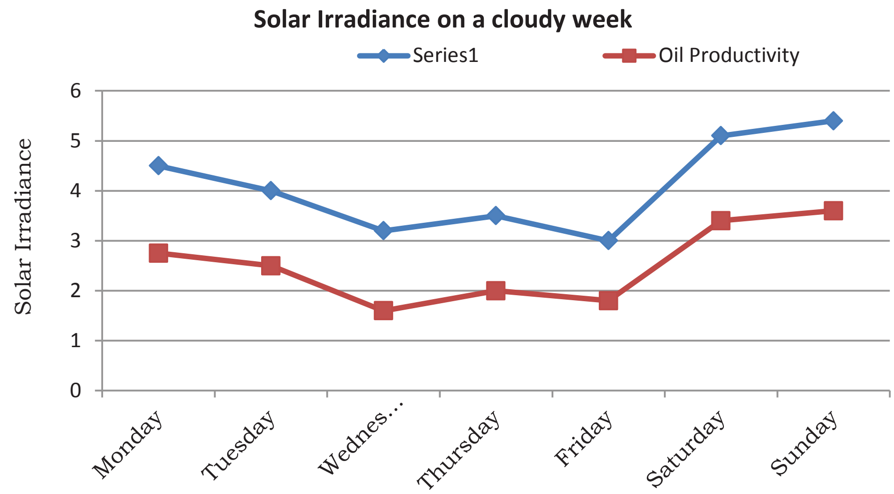


Figure. 5.15. Effect of cloudy days and irradiation on oil production.

The associated instrumentation control system of crude oil heating system has been continuously supporting to protect from gas leakage accident and production loss, in the event of solar power loss The Figure 5.16 shows the progress of crude oil treatment using prototype.

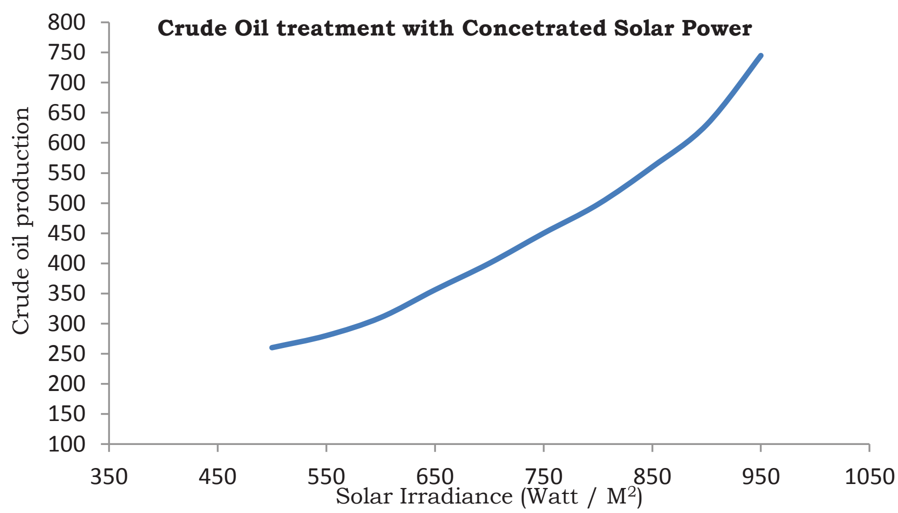


Figure. 5.16. Crude Oil treatment with CSP prototype

The estimation and computations for the conceptualized model shows that by the utilization of the parabolic dish double modular concentrator, it is possible to achieve the temperature of the water that reaches the vaporization temperature, which supports the various technical purposes.

The CSP model is expected to support the carbon neutrality mission, by industrial sectors. During the pilot study it is estimated that air venting of CO_2,

CH_4 and N_2O is reduced in the range of 30-35% [94]. It has been also estimated that there would be 40% reduction in NG consumption with this hybrid system.

5.4 Crude Oil heating applications utilizing Bio-Solar hybrid

The ultimate objective of producing algal bio-gas has been analyzed from cultivation and harvesting biomass. The biomass generation has been based on CO_2 concentration in the media and depends upon maximal growth rate of algae. Therefore, an optimal pH value and CO_2 concentration are required to be maintained. Experimental validations performed at location 3 have reported that algal strain Chlorella sp. was used pure CO_2 in vent gas.

Following the above study, Growth of Chlorella sp at pH 7.5 has been studied in the presence of air bubbling by aerator and growth in the presence of vent gas while purging. The growth results have been shown in Figure 5.17.

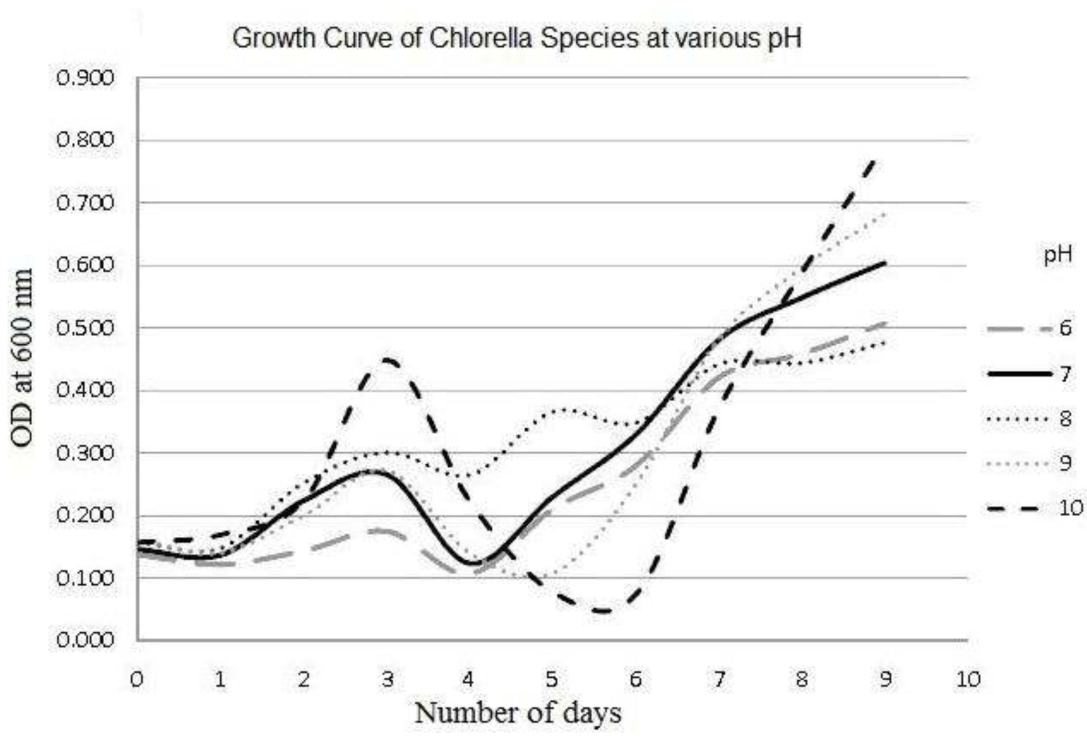


Figure. 5.17. Growth studies of Chlorella at varying pH at location 3

As shown in Figure 4.3, medium has been pumped into the CO_2 absorption column per day and has been continuously purged with the industrial vent gas. The CO_2 absorption column is completely closed so as to collect the outlet gas and analyze so as to quantify the CO_2 absorbed in the medium. The growth and cultivation of algae has been monitored in the pilot raceway. The growth results have been shown in Fig 5.18 [79].

The increase in Optical density (O.D) from 0.001 to 0.402 has been reported which actually interprets the growth of the selected algae. The pH of the medium decreased from pH 11 to around 6.7 in the CO_2 absorption column due to purging of vent gas containing CO_2. Finally the yield of Chlorella species has been found to be 18g/m^2/day. The algal growth in raceway pond and dominant algae growth has been shown in Figure 5.19(a) and (b) respectively.

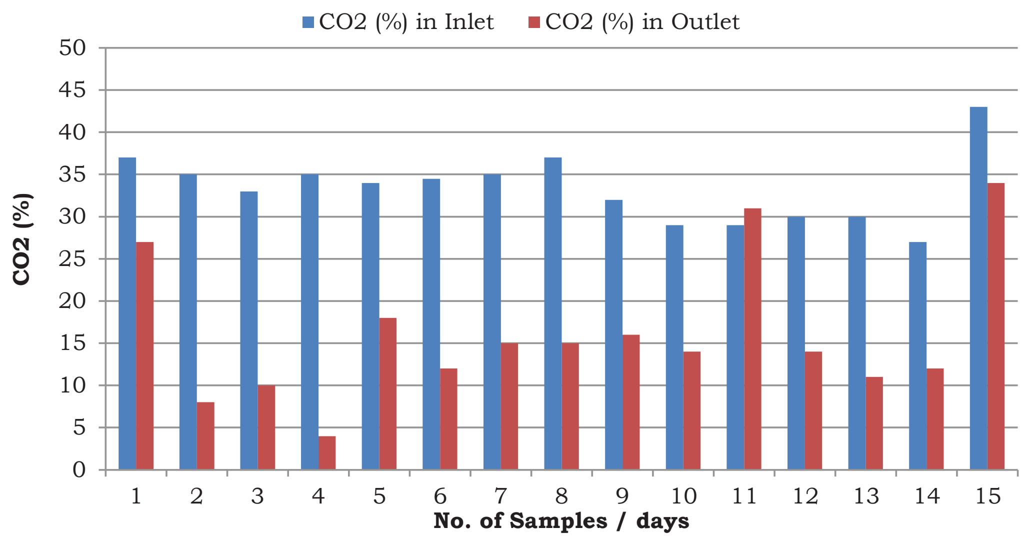
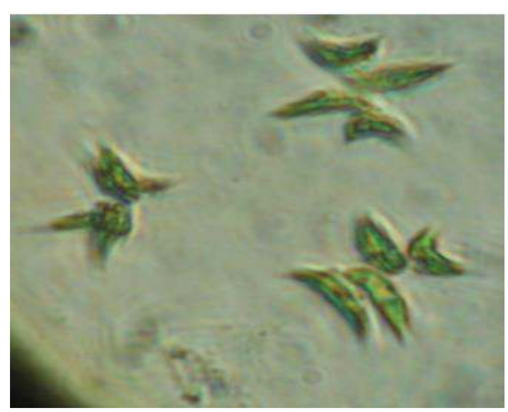


Figure. 5.18. CO_2 absorption studies on industrial vent

The objective of bio-methane (Bio-gas) potential with industrial sludge (waste water from oil industry) from an anaerobic pilot reactor enriched on ethanol has been used as inoculum with 40gm/L. These reactors have been provided with synthetic growth medium containing nutrients, trace elements and bicarbonate. The reactors has been purged with N_2 gas at the beginning of the experiment and mixed manually once a day.



(a) Algal growth in the raceway pond (b) Dominant algae

Figure. 5.19. (a) Algal growth at raceway pond (b) Dominant algae

Biogas production and composition have been measured during periodical gas samples, composition analysis was done using gas chromatography (Chemito Gas Chromatography). The digestion results suggested that the mixed algae consortium requires longer time to complete the digestion and Chlorella sp. has higher biogas yields than mixed algae population. The average methane content of the biogas for Chlorella has been found in the range *50- 55%.*

During the process with low loading rate and high hydraulic retention time, the methane yield (CH_4) maximal till 386 L CH_4/gm of Chlorella, whereas 228 L CH_4/gm has been reported for mixed algae after deducting the values of negative control, shown in Figure 5.20.

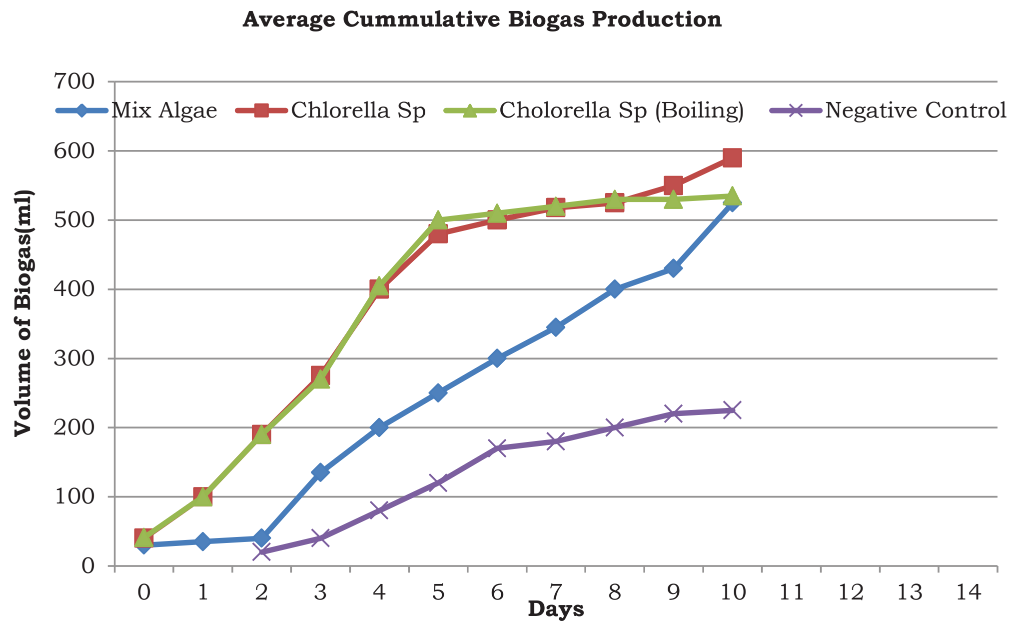


Figure. 5.20. Average cumulative biogas production during pilot study

The biogas produced has been utilized for combustion purpose and substitute the NG being used for the crude oil heating. The present crude oil heating arrangement needs some electrical power requirements. Some artificial lighting equipment has been used by the hybrid systems, which are fed by electricity generated by another PV system.

The average cumulative biogas production during this pilot study has been shown in Figure 5.20 and the yield of Chlorella sp. is about 18gm/m^2/day which on anaerobic digestion yields about 386 L CH_4/gm. The hybrid solution has also estimated the total power requirement and compared with alternate possible methods for crude oil heating.

5.5 Alternate options for Crude Oil Heating and Comparison

The present research work also explored the possibilities of alternate options for crude oil heating as shown in Figure 5.21 and concluded with a comparative analysis.

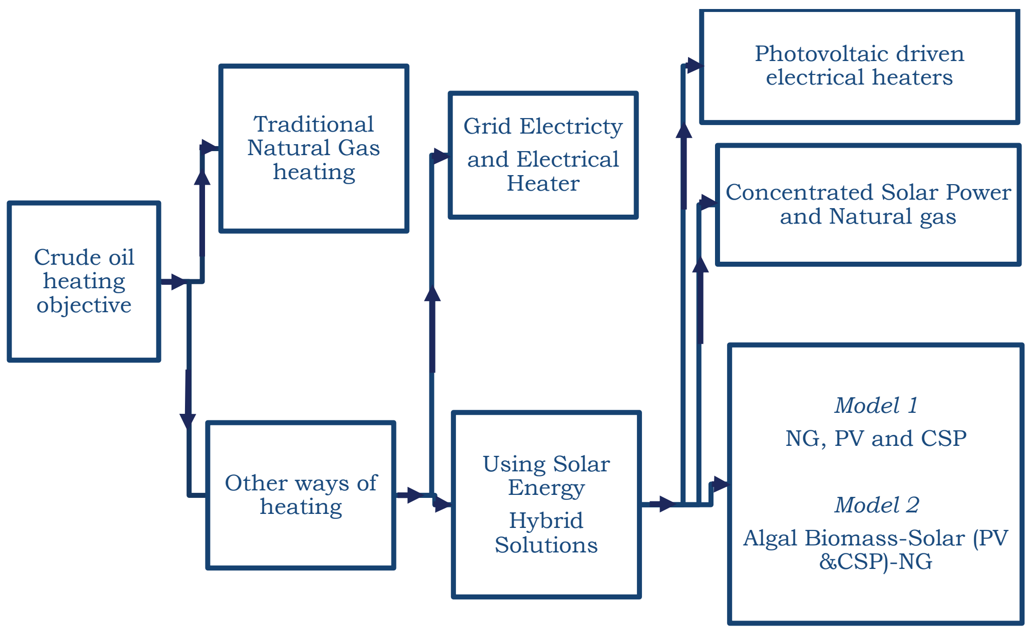


Figure. 5.21. Alternate options for crude oil heating

5.6 Comparative analysis between alternative solutions

The average temperature and heat (power equivalent) required for a minimum capacity heater treater are 90°C and 1400 kW respectively for the location [95]. The cost estimation and comparative analysis between alternative solutions for crude oil heating has been deliberated and summarized in Table 5.6. The detailed heat calculation at location 3 has been based on data inputs as in Table 3.6 and 4.1. The calculations are as under:

1. Total amount of crude oil(in kg), which is to be heated

   = Total flow of crude x Specific gravity of Crude at 15°C

   = 10 m^3/hr * 0.85 x 1000= 8500 Kg= 8500 x 10^3 g
2. Heat energy required to heat(in Joules) above 8500 KG of crude

   = m x S x T, T is 80-30=50{Initial temperature-30°C }

   = 8500 x 10^3 g x 2.13 J/ g°C X 50°C=905250 KJ

   Where: m=8500 Kg, S= 2.13 J/g°C, T=50°C
3. Heating up crude of 8500 Kg in one hour, requires 905250 kJ of energy and daily equals to 21726000 kJ
4. Approximate 251KWh of electricity is the requirement.

5. The prevalent grid electricity tariff @ Rs 8.20 per unit at location 2.
6. The amount of total gas being used at location for one heater unit is 1226640 Standard Cubic Meter (SCM).

The costing calculations has been made on four basic parameters, as summarized in Table 5.6, however there are many other tangible parameters, which would further tune of the costing of the system.

Table 5.6. Cost detailing of NG based Crude Oil Heating in ONGC

Parameters	Costing	Denotation
Cost of Natural Gas	Rs 8.2 X 1226640	A
Manpower cost(*)	@ 25% of A	B
Land requirement	@20% of A (One time cost)	C
Operation and Maintenance cost	@40% of A (Highest and variable after life cycle of various equipment's)	D

(*) The percentage costing of manpower, Land and O&M are based of internal documents of prevailing rates in ONGC for the year 2014-15) Also internal NG price is half of market prices for heater treater

5.7 Techno-Economic analysis of Bio-NG-PV-hybrid system

The mass-energy balance study has been chosen on large scale testing unit and found that the cultivation/ harvesting have been found at the rate of 30% to produce the dry algal biomass. Various nutrients like nitrogen and phosphorus found in the range of 0.025 to 0.005 kg per day respectively. Also during the process, considerable amount of water is recycled. The electrical energy required for the detailed supply chain is around 215.5 kWh units per day. The hybrid system uses PV based electricity for bioreactor and digester system in addition to requirement of energy for other associated system. The solar irradiance predicts around 450 kWh AC of electricity and accordingly the PV system has been modeled.

Economic feasibility has been always a critical factor that determines commercial applicability of any engineering system. Generally, the biogases produced from digesters used locally in cogeneration units or heat requirement based equipments. This hybrid model would be utilized for many years ahead and could support in sustainable future of reduced emissions. The associated other renewable energy sources like solar PV or concentrated solar power would further strengthen the purpose of heat generation and its direct utilization as well as electricity production. Biogas could be blended with NG in crude oil heating purpose and maintain the supply chain of gas supply to customers. In order to estimate the detailed costing of hybrid system, standard costing and regulations released from Central Electricity Regulatory Commission has been also referred.

Table 5.7. Hybrid System-Economic analysis and comparison

Parameters	**Comparison between two options**	
	Bio-PV fed algal system	Natural Gas fired crude oil system
Capital cost(INR) and its indexation	3430000	2450000
Accelerated depreciation(%)	5.83 to 1.54	4.32
Capacity utilization factor (CUF)	19	23
Useful life (years)	20-25	25-30
Tariff period (INR per unit)	INR 5.2	INR 8.2
Return on equity(%)	@ 24%	@12%
Interest on loan and capital(%)	8-13.5 %	11%
Operation and maintenance (%)	8-10%	15-20%
Capital expenditure(CapEX)		
PBR unit(INR) Approx.	1245345.00	Not applicable
PV based system	200000	Not applicable
Centifuse and dryer System	115000	Not applicable
Control system	243500	Not applicable

The evaluation of economic calculations and capital cost have been focused using CERC regulations including indexation mechanism, which accounts for wholesale price index of machinery and variable electricity tariffs [96]. These regulations attract other tangible parameters like legal financial penalties beside the fiscal incentives to undertake commercial project activities improve the payback period of the work. It has been reported that the additional cost on biogas processing and utilization is in the range of 11-16 percent of total capital cost [97]. Thus hybrid module has been emerged more attractive system on merits.

With the proposed model, having limited available land area for the microalgae cultivation next to the plant, the dissolved CO_2, could be transported by pipeline to other locations for algae cultivation. After use, the filtered and

CO_2-lean could then be returned to the capture facility for reuse in the CO_2 absorber. CO_2 capture and intermediate storage concept is currently being demonstrated at the Global Algae Innovations facility in Hawaii (Corpuz 2015)[98]. The comparative analysis of Algal-Solar (PV&CSP) and NG hybrid system has been generated using the various industrial real data compilation and shown in the Figure 5.22.

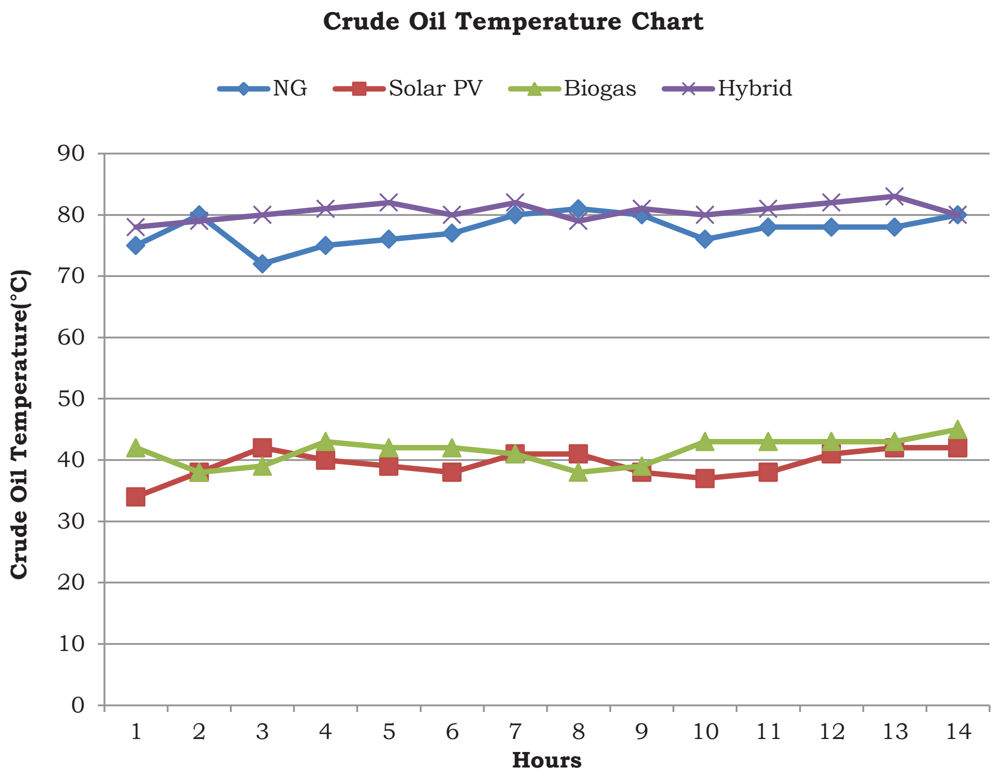


Figure. 5.22. Comparison of required heat by NG, PV, Biogas Hybrid

The cost estimation and commercial viability studied summarized at Table 5.8 suggests that hybrid solution has been an effective and efficient solution for crude oil heating. The performance of the prototype has been evaluated, and proposes that the prototype would provide the benchmark data on building solar thermal crude heater. It has been estimated that Bio-Solar-NG hybrid system at one location has the potential to reduce Natural Gas consumption by 432 Million Standard Cubic feet. Similar model could be used for all ONGC locations (more than 300 installation of different capacity), leading to cost saving of approx. 76 Million Dollars annually.

The Capex of the Bio-PV hybrid system is higher than NG based system due to expensive PV panel equipments, Biogas auxiliaries and associated control and instrumentation system. The techno-commercial study also suggest that the scaled up hybrid model is a technically feasible solution and with adequate carbon sequestration from gas processing complex at location 2. Considering both Operational Expenditure (OpEx) and revenue, it is apparent that the Bio-Solar-NG hybrid solution has been emerged technically as well as economically feasible.

Table 5.8. Selection of suitable technology for crude oil heating

Cost	NG based (Equivalent Electricity)	Grid power based	Solar PV and Electrical heater	Bio-Solar hybrid
Fuel	A	A/2	2*A + A/10)	3A+ A/3
Equipment and Assembly	-	-	3*A-Solar	5*A CSP and Biomass
Manpower	B	0.1*B	0.25*B	0.1*B
Land (One time)	C	C/5	1.5 *C	1.5*C
Operation & Maintenance	D	D/2	D/2	D/5 (Lowest)

Inclusion of other tangible benefits arises from RECs financial incentives [99] and Clean Development Mechanism (CDM) would make the pay back more attractive [100].

5.8 Summary and Conclusions

The hybrid model has been attempted with interdisciplinary studies on Carbon Capture and Optimization of Solar energy in PV and Solar thermal. This chapter suggested that the envisaged Algal-Solar (PV & CSP)-NG hybrid model has been technically and as well commercially feasible solution in Oil and Gas industries. The green energy concept of the work would have additional financial and mileage benefits in association with REC mechanism and CDM registration.

The next Chapter presents the conclusions and suggestion for future work.