Modelling and Analysis of Energy Systems

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Modelling and analysis of receiver – heat loss, steady state hydrothermal analysis of absorber tubes

Experimental validation
#2. System Design/Analysis

Energy Efficiency: Model Based Benchmarking

- **Surveys of existing models of process**
  - **Understanding basics**
    - Defining system boundary
    - Writing fundamental equations governing process
    - Decide assumptions
  - Identifying empirical correlations for process

- **Energy intensive process**

- **Study of actual process operation (process audit)**
  - Operating procedure and practices
  - Control strategy and instrumentation
  - Process constraints
  - Logbook parameters

- **Data from industrial process**

- **Model development**
  - Divide process into sub-models
  - Identify input / output parameters for sub-models
  - Identification of design and operating variables
  - Developing linkage between process parameters and energy consumption

- **Developing experimentation protocols**

- **Experimentation**

- **Validation of model**

- **Refinement of model**

- **Target energy estimation**

- **Parametric analysis**

- **Usage of model**

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Flowchart Diagram:

1. **Survey of existing models of process**
   - **Understanding basics**
     - Defining system boundary
     - Writing fundamental equations governing process
     - Decide assumptions
   - Identifying empirical correlations for process
2. **Energy intensive process**
3. **Study of actual process operation (process audit)**
   - Operating procedure and practices
   - Control strategy and instrumentation
   - Process constraints
   - Logbook parameters
4. **Data from industrial process**
5. **Model development**
   - Divide process into sub-models
   - Identify input / output parameters for sub-models
   - Identification of design and operating variables
   - Developing linkage between process parameters and energy consumption
6. **Developing experimentation protocols**
7. **Experimentation**
8. **Validation of model**
9. **Refinement of model**
10. **Target energy estimation**
11. **Parametric analysis**
12. **Usage of model**
#2 Glass Furnace - Model flow diagram

**Design variables**
- Furnace operating pressure
- Cooling air velocity
- Number of burner
- Burner air nozzle diameter
- Fuel consumption
- Ambient conditions
- Fuel composition
- Glass composition
- Moisture in batch and cullet
- Cullet %
- Glass draw
- Furnace design capacity
- Melting area
- Furnace design details
- Color of glass

**Fuel stoichiometric calculation**
- Fuel calorific value
- Fuel composition

**Glass reaction calculation**
- Glass outlet temperature
- Oxygen % at regenerator outlet

**Furnace air / flue gas leakage calculations**
- Gap in flux line
- Gap near burner

**Combustion zone stoichiometric calculation**
- Oxygen % at furnace outlet
- Flue gas leakage
- Combustion species

**Regenerator calculation**
- Heat loss from flue gas leakage
- Mass of air
- Mass of flue gas

**Furnace geometry calculation**
- Furnace design characteristics
- Furnace geometry
- Furnace outlet temperature

**Heat of reaction and heat carried by glass**
- Heat of reaction for glass
- Heat carried with glass
- Heat loss batch gas
- Heat carried with glass
- Heat loss from batch moisture

**Furnace wall losses**
- Heat loss from furnace area wall

**Guess for total heat added**
- Total heat added in furnace
#2 Furnace measurement

<table>
<thead>
<tr>
<th>Measurement location</th>
<th>Type of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Oxygen %, Pyrometer checkers surface temperature</td>
</tr>
<tr>
<td>2</td>
<td>Oxygen %, Flue gas temperature</td>
</tr>
<tr>
<td>3</td>
<td>Oxygen %, Flue gas temperature</td>
</tr>
<tr>
<td>4</td>
<td>Oxygen %, Skin temperature</td>
</tr>
<tr>
<td>5</td>
<td>Pyrometer checkers surface temperature</td>
</tr>
<tr>
<td>6</td>
<td>Velocity of air at the suction of blower</td>
</tr>
<tr>
<td>7</td>
<td>Outside wall temperature for crown and side wall</td>
</tr>
<tr>
<td>8</td>
<td>Pyrometer glass surface temperature</td>
</tr>
</tbody>
</table>
#2 Model results: Actual SEC

![Flow diagram of energy loss and recovery in a furnace.]

- **Energy introduced in furnace**: 100% (4267)
- **Heat carried in glass**: 38.2% (1628)
- **Heat carried in regenerator from flue gas**: 0%
- **Heat of glass moisture**: 6.1% (261)
- **Heat of glass reaction**: 5% (212)
- **Batch gas losses**: 2% (84)
- **Heat lost in moisture**: 9.7% (414)
- **Heat lost steel Heat loss from superstructure/furnace opening**: 2.8% (118)
- **Heat lost in cold air ingress**: 0.7% (45)
- **Heat loss from flue gas**: 29.4% (1256)
- **Heat loss from furnace opening**: 1% (45)
- **Furnace wall losses**: 38.2% (1628)
- **Regenerator wall losses**: 2% (84)
- **Heat recovery in air heating**: 33.8% (1485)
- **Heat carried in glass**: 38.2% (1628)
- **Heat carried in regenerator from flue gas**: 0%
- **Heat of glass moisture**: 6.1% (261)
- **Heat of glass reaction**: 5% (212)
- **Batch gas losses**: 2% (84)
- **Heat lost in moisture**: 9.7% (414)
- **Heat lost steel Heat loss from superstructure/furnace opening**: 2.8% (118)
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- **Regenerator wall losses**: 2% (84)

**Graph:**

- **SEC (kJ/kg)**
- **Furnace number**

**Legend:**
- Target SEC
- Actual SEC

**Note:** The graph shows the variation of SEC across different furnaces.
#2 Input Output Flow Diagram - Mining

**MINING UNIT BOUNDARY**

**INPUTS**
- Unexcavated ore
- Water
- Energy requirements
  - Electricity
- Diesel
- Others
- Engine oil
- Lubricating oil
- Explosives

**OUTPUTS**
- Finished ore
- Gas emissions
  - CO, CO2, NOx
- Dusts
- Dewatering/Depositing
- Waste/Overburden

**INPUT**
- 152 MJ/ton (100%)

**OUTPUTS**
- Dragline (14.57%)
- Pumping (17.85%)
- Shovel (2.42%)
- Dump trucks (32.52%)
- Excavators (20.43%)
- Lighting (3.01%)
- Coal handling (5.72%)
#2 Mine Transport Model

**Variation of SFC with pay load**

- Actual SFC
- Model SFC
- Linear (Actual SFC)

**Fuel saving potential**

In transport = 17%

**Comparison of Model result with actual data**

**Variation of material handled and SFC with speed**

- Material handling (t/h)
- SFC (g/t)

- Optimal value: Loading (L), Unloading (U), Optimal (O), Minimum SFC (M), Maximum SFC (Q)
#2
Water and energy assessment

\[
SWR = \frac{W_r(t)}{Q_\text{oore}(t)}
\]

\[
SEC_{\text{pump}} = \frac{E(t)}{Q_\text{oore}(t)}
\]

IFD for water and energy assessment

Note: The numbers in the IFD shows the equation numbers of the model
#2 WATER AND ENERGY ASSESSMENT RESULTS

Variation of energy, water and excavation index

Water inflows and removal rate with time

Seasonal variations 2009-10(1) and 2010-11(2)

Variation of SEC and SWR with coal production

Variation of energy, water and excavation index
#2 National Solar Thermal Power Facility – Consortium supported by MNRE and led by IIT Bombay

![Schematic of 1 MW Solar Power Plant]

- **Parabolic Trough Solar Field**
- **Linear Fresnel Reflector Solar Field at Gwalpahari site**

**Simulator snapshot**

**Consortium Members**

- KIE Solatherm
- Ministry of New & Renewable Energy
- TCE
- Tata Power
General User Inputs

- Site data – lat., long., insolation, temperature, wind speed, rainfall

Solar Models

- Data library, interpolation modules, empirical models

Fluid Models

- Fluid properties – water, thermic fluids, etc.
- Library of fluid properties

Equipment Models

- Characteristic models – solar collectors, pumps, heat exchangers, turbines, etc.
  \[ \eta = f (m_{in}, T_{in}, IT/B, V_{wind}) \]

Flow sheeting

- User defined connectivity for equipment through GUI. Alternative configurations can be studied.

Equation builder & Solver

- Based on user defined PFD – mathematical models
- User defined time steps, time horizon. Pseudo steady State simulation – sequential modular approach

Simulation output

- System performance including cost of overall system
User Interface: Main Window

Open Sample Process Flow Diagram
Sample PFD1  Thermo Fluid based Indirect Steam Generation Power Plant with Regeneration
Sample PFD2  Thermo Fluid based Indirect Steam Generation Power Plant with Reheat
Sample PFD3  Thermo Fluid based Indirect Steam Generation Power Plant with Reheat and Multiple Regeneration
Sample PFD4  Direct Steam Generation Power Plant (assisted by auxiliary boiler) with Regeneration
Sample PFD5  Direct Steam Generation (assisted by auxiliary boiler) for Process Heat Application
Sample PFD6  Direct Steam Generation (assisted by auxiliary boiler) for Process Heat Application

Getting Started

- Open any of the six sample process flow diagram for steady state simulation.
- Double click the equipment and stream node to know its parameters and to make changes.
- Parametric study can be done by changing the system parameters, such as, location, stream parameters, control variable, equipment model parameters, etc.
- Save the file (even if no changes are made) and click 'Run Simulation' for getting results.
- The results will be displayed in tabular format.

* Usage of this Software is governed by the license agreement
Generation of user defined process flow diagram using user interface
Results display in tabular form

Results display in graphical form
House Architecture

Integration of traditional knowledge with modern simulations
2 bedrooms with modular furniture
Steel based prefab construction
Insulated wall panels for thermal comfort
Extensive daylighting provision

Synergy of Vastu Shastra and Passive Solar Architecture

<table>
<thead>
<tr>
<th>Position</th>
<th>1st pref.</th>
<th>2nd pref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawing and Dining Room</td>
<td>E</td>
<td>N</td>
</tr>
<tr>
<td>Kitchen</td>
<td>SE</td>
<td>NW</td>
</tr>
<tr>
<td>Master Bedroom</td>
<td>SW</td>
<td>S</td>
</tr>
<tr>
<td>Kids Bedroom</td>
<td>NW</td>
<td>SW</td>
</tr>
<tr>
<td>Main Entrance</td>
<td>NE</td>
<td>E</td>
</tr>
<tr>
<td>Bathrooms</td>
<td>NW</td>
<td>W</td>
</tr>
</tbody>
</table>
Simulation and design
Energy saving opportunities

Energy efficiency opportunities exist as thermal and lighting loads high

Use of simulation tools for window sizing, insulation sizing, overhangs and daylighting

Load reduction by 65% (AC case) & 63% (non AC case) for Mumbai

Usual Non AC for Mumbai (54 kWh/m\(^2\)-year)

Usual AC for Mumbai (68 kWh/m\(^2\)-year)

Simulation use to reduce cooling load
Electrical Energy Balance

Contest Criteria:
- Load Consumption per unit area
- Positive Electrical Energy Balance
- Temporary Generation-Consumption Correlation
- Maintaining Network Load State
- Managing Power Peaks

Performance:
- PV Supply = 281 kWh, Demand = 146 kWh
- Net Energy Positive, 135 kWh in 12 days
- Energy payback analysis% for PV = 2.4 years
Sizing of Photovoltaic-Battery Systems

Objective:

To arrive at the set of all feasible configurations (Array rating and Battery capacity) to meet a given demand following a time-series simulation of the system.
Photovoltaic-Battery System Sizing (Deterministic Approach)

Inputs: Hourly solar insolation data, Hourly load data, Photovoltaic system efficiency, Power conversion efficiency

Estimation of the solar insolation incident on the array

System simulation to obtain the minimum array size and the corresponding battery capacity

Calculation of the minimum storage capacity for different array sizes greater than the minimum

Plot of sizing curve and the identification of the design space
Graphical representation

- Sizing curve for given solar insolation profile, load curve and system characteristics
Photovoltaic-Battery System Sizing (Example)

remote location in Sagar island, West Bengal

- Demand profile (average day)
- Solar insolation Average: December

![Graphs showing solar insolation and load profile]

- Minimum array rating
- Sizing curve
- Feasible region
- Infeasible region
Sizing methodology for a PV-battery system employing DSM

Inputs for load model
- Number of households
- Appliances and their technical characteristics
- Share of appliances
- Agricultural pump sets and ratings
- Commercial loads and technical characteristics

Usage pattern (Time of use) (Daily and seasonal variation)

Load model
- Residential electricity consumption (kWh) (2)
- Agricultural electricity consumption (kWh) (4)
- Commercial electricity consumption (kWh) (6)
- Total electricity consumption (kWh) of the area (7)

Solar PV and battery model. (8), (12)-(13)
- Solar radiation data
- Ambient temperature data
- Technical specifications of PV modules
- Technical specifications of battery
- Increment number of PV panels and battery capacity
- Calculation of Reliability (LOLE) for number of PV panels and capacity of battery. (15)
- LOLE ≤ LOLE_d
  - YES
  - Calculation of ALCC and CGE for different ratings of PV, and battery. (16) - (18)
  - NO
- CSE_i ≤ MCOE
  - YES
  - Available Demand side option
  - NO
- All DSM options integrated?
  - YES
  - Optimum configuration of PV-battery ALCC CGE
  - NO

Inputs for supply side model
- DSM options for end use loads from literature. DSM_i, i=1, 2, 3, ..

i=i+1
<table>
<thead>
<tr>
<th>Sector</th>
<th>Load</th>
<th>% contribution to total load</th>
<th>EE option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>Lighting</td>
<td>41.1</td>
<td>60W incandescent to 15W CFL</td>
</tr>
<tr>
<td></td>
<td>Fan load</td>
<td>12.7</td>
<td>Ceiling Fan of 65W replaced by BLDC fan</td>
</tr>
<tr>
<td></td>
<td>TV load</td>
<td>2.1</td>
<td>19 inch CRT TV replaced with 22W LCD</td>
</tr>
<tr>
<td>Agricultural</td>
<td>Motor &amp; pump loads</td>
<td>29.55</td>
<td>Energy efficient motor-56%</td>
</tr>
<tr>
<td>Community</td>
<td>Street lighting</td>
<td>8.45</td>
<td>HPSV lamps by LED lighting</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Annual energy savings(kWh/year)</strong> 25610</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load</th>
<th>EE option</th>
<th>Demand savings(kWh/year)</th>
<th>Hours of operation/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lighting load</strong></td>
<td>Replacing Incandescent with 15W CFL</td>
<td>13140</td>
<td>1460</td>
</tr>
<tr>
<td></td>
<td>Replacing CFL with LED</td>
<td>2044</td>
<td>1460</td>
</tr>
<tr>
<td></td>
<td>Replacing with 8W LED</td>
<td>15184</td>
<td>1460</td>
</tr>
<tr>
<td><strong>FAN load</strong></td>
<td>Replacing with 35 W BLDC motor</td>
<td>3240</td>
<td>1460</td>
</tr>
<tr>
<td></td>
<td>Replacing with energy efficient blades(60W)</td>
<td>540</td>
<td>1460</td>
</tr>
<tr>
<td><strong>TV</strong></td>
<td>Replacing with 19 inch LCD TV</td>
<td>635</td>
<td>1095</td>
</tr>
<tr>
<td><strong>Agriculture</strong></td>
<td>Energy efficient motor-56%</td>
<td>5748</td>
<td>2008</td>
</tr>
<tr>
<td><strong>Street lighting</strong></td>
<td>HPSV lamps by LED lighting(40W)</td>
<td>2847</td>
<td>4745</td>
</tr>
</tbody>
</table>
Total demand summer (kWh)

Total demand Winter (kWh)
### #3 System Integration – Wind – Tamil Nadu

#### Hourly variation of wind power

#### Monthly variation of wind energy generated
Input n and n discrete wind capacities

Select major sites

Extrapolated hourly wind power generation

Effective load curve

Divide load curve into 100 MW bins

Record number of hours in each bin

Frequency distribution of load over the year

Sum up to obtain annual load duration curve

Evaluate for n discrete wind capacities

Calculate effective base and peak load savings from different LDCs obtained

Wind turbine characteristics

Hourly load curve

Hourly wind speed

Installed capacity of wind power

#3
#3 Impacts on LDC

![Graph showing impacts on LDC](image)
Model for Potential Estimation of Target Area

Target area
Weather data, area details

Identification and Classification of different end uses by sector (i)

Residential (1)
Classification based on factors* (j)

Hospital (2)
Nursing Homes (3)
Hotels (4)
Others (5)

Sub-class (i, j)
Single end use point

Technical Potential
Economic Potential
Market Potential

No. of end use points

Technical Potential
Economic Potential
Market Potential

Potential for end use sector (i = 1)
Potential for i = 2
Potential for i = 3
Potential for i = 4
Potential for i = 5

POTENTIAL OF SWHS IN TARGET AREA
Technical Potential (m² of collector area)
Economic Potential (m² of collector area)
Market Potential (m² of collector area)
Energy Savings Potential (kWh/year)
Load Shaving Potential (kWh/hour for a monthly average day)

* Factors affecting the adoption/sizing of solar water heating systems
Load Curve Representing Energy Requirement for Water Heating

- Typical day of January
- Typical day of May

Energy Consumption (MW)

Hour of day

Total Consumption = 760 MWh/day
Total Consumption = 13900 MWh/day
Total Consumption = 14300 MWh/day

Total Electricity Consumption of Pune
Electricity Consumption for water heating of Pune
Diffusion of SWH

Solar Water Heating Capacity (collector area in million sq. m.)

- Actual installed (million sq. m.)
- Potential 140 million sq. m.
- Potential 60 million sq. m.
- Potential 200 million sq. m.
- Extrapolated Potential (million sq.m.)

Estimated Potential in 2092 = 199 million m²
#4 PLAN LAYOUT

## Area Estimation Block
- Building Footprint Ratio
- GIS Tools
- Satellite Image Samples
- Literature
- Building Footprint Area (BFA)
- PVA Ratio
- PVA

## Insolation Estimation Block
- Hourly DNI, DHI & Diffuse values
- Liu-Jordan Model
- Design Parameters

## Panel Efficiency
- Panel Efficiency
- Solar Panel Database
- Performance Ratio

## PV Device & System Block
- Panel Efficiency
- PTC
- Existing Energy Requirement & Consumption Scenario
- Technical Potential
- Generation Profile
- Capacity Factor
- Ambient Temperature
- PVSyst Simulations
A portion of the ELU map of Ward A of MCGM

Corresponding Satellite Imagery for the area from Google Earth

Analyzed in QGIS 1.8.0
To determine -Building Footprint Ratios -Usable PV Areas For Sample Buildings
Jan, 2014 Typical Load Profile vs PV Generation

Capacity Factor for Mumbai

- 1-Axis Tracking
- Fixed Tilt @ 19 deg.
- Annual Average with 1-Axis Tracking

Capacity Factor for Mumbai
Biomass to Hydrogen Conversion

Biomass to hydrogen conversion routes

- Thermochemical
  - Pyrolysis/Gasification
  - Biophotolysis (direct/indirect)
- Biological
  - Dark fermentation
  - Photofermentation

- #1 Dark Fermentation
- #2 Photo Fermentation
- #3 Two-stage fermentation process
- #4 Biocatalysed Electrolysis

Input feedstock – Sugarcane juice
Results (without by product use)

<table>
<thead>
<tr>
<th>Process</th>
<th>Case 1: Without by-products</th>
<th>GHG (kg CO₂)</th>
<th>Non-renewable energy use (MJ)</th>
<th>Energy efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam methane reforming</td>
<td></td>
<td>12.8</td>
<td>188</td>
<td>64</td>
</tr>
<tr>
<td>Dark-fermentation</td>
<td></td>
<td>5.5</td>
<td>61.7</td>
<td>9.6</td>
</tr>
<tr>
<td>Photo-fermentation</td>
<td></td>
<td>3.5</td>
<td>40.1</td>
<td>25.6</td>
</tr>
<tr>
<td>Two-stage process</td>
<td></td>
<td>3.4</td>
<td>39.3</td>
<td>27.2</td>
</tr>
<tr>
<td>Biocatalyzed electrolysis</td>
<td></td>
<td>5.3</td>
<td>64.8</td>
<td>25.7</td>
</tr>
</tbody>
</table>
Methodology for analysis

- Life cycle Approach
- \( NER = \frac{E_{\text{out}}}{E_{\text{in}}} \)

If \( NER > 1 \), Replacement viable

If \( NER < 1 \), Replacement not viable

- \( \text{CRF}(d, n) = \left[ d \cdot (1+d)^n \right] / [(1+d)^n - 1] \)
- \( \text{ALCC} = AC + C_0 \cdot \text{CRF}(d, n) \)
- \( \text{NER} \) (Net Energy Ratio)
- \( \text{ALCC} \) (Annualized cost)
- \( \text{CRF} \) (Cash recovery factor)

Secondary Energy
Primary Energy
Renewable Energy
Jatropha and Karanja Analysis results

Jatropha, Different yield levels (tonnes/ha)

Karanja, Different yield levels (tonnes/ha)

Rs. 33-36/kg  2007 values

Rs. 21-25/kg
Sustainability Analysis

- Process flow charts
- Sizing of different equipment required
  - Inventory (process energy and material) to produce one unit of output
    - Total primary energy required to produce required process energy and materials
      - Total GHG emissions in producing process energy and materials (using emission factors)
        - GHG emissions
      - Classification of total primary energy into non-renewable and renewable energy
        - Non-renewable energy use
      - Cost of different equipment and material required, discount rate, life of the equipment
        - Life cycle cost
    - Life cycle cost
  - Materials and other resources such as water, land etc required to produce 1 kg of hydrogen

- Resource constraint
  - Amount of material and other resources required to meet the current demand
Resource constraint

- Material supply constraint
  - Area
    - Annual requirement/Reserve
    - Area required/Available land area
  - Annual requirement/Reserve
- Material constraint
  - Other constraint
    - Technical constraint, water for biomass based systems etc.
  - No constraint
#6 Decomposition Analysis

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Change per year (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Emissions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intensity</td>
<td>-0.10%</td>
<td>3.88%</td>
<td>0.62%</td>
<td>-1.97%</td>
</tr>
<tr>
<td>Change in Structure</td>
<td>0.83%</td>
<td>0.75%</td>
<td>0.70%</td>
<td>0.07%</td>
</tr>
<tr>
<td>Change in energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>intensity of GDP</td>
<td>-1.54%</td>
<td>-0.13%</td>
<td>-2.70%</td>
<td>-2.99%</td>
</tr>
<tr>
<td>Change in Emissions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intensity of Energy</td>
<td>0.74%</td>
<td>3.10%</td>
<td>3.35%</td>
<td>1.57%</td>
</tr>
</tbody>
</table>
- High Industry Baseline
- High Services Baseline
- 25% Reduction in Emissions Intensity of GDP
- 25% Deviation from BAU Emissions
- Constant Emissions between 2008 and 2030
Summing Up

- Models – representation of reality
- Can help in more efficient component, system design
- Can help identify future sustainable routes, assess impacts
- Blend of modelling, prototypes – sustainable systems of the future
- Improved decision making, better choices
- Value judgements - trade-offs between criteria
- Optimising/ Satisficing
Acknowledgment

Santanu B.
Faculty

Suneet Singh
Faculty

Doola Suryanarayana
Faculty

Vishal S.
Faculty

Arun P.
Ph.D. - 2009

Indu Pillai
Ph.D. - 2008

Tejal Kanitkar
(Ph.D.)

Lalit K Sahoo
(Ph.D.)

K. Aravind Kumar
(Ph.D)

Jay Dhariwal
(Ph.D)

Rhythm Singh
(Ph.D)

Balkrishna Surve
Project Assistant

National Solar Thermal Power Project – Team
Team Shunya – IITB / Rachana Sansad

Thank you


