Modelling of Energy Systems

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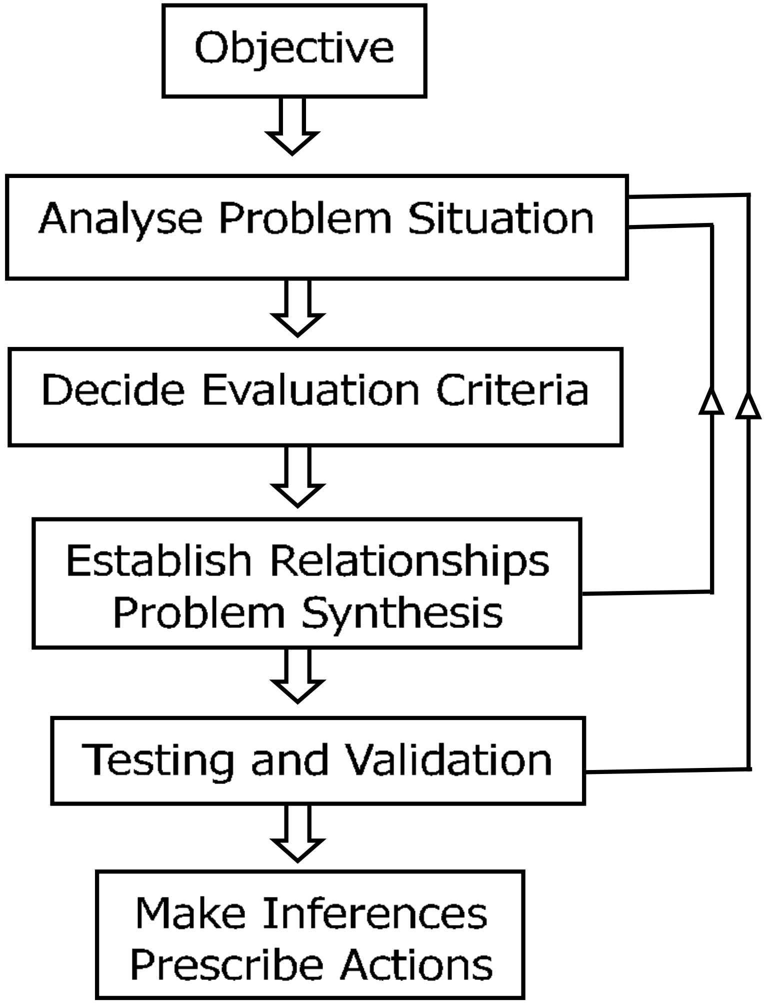
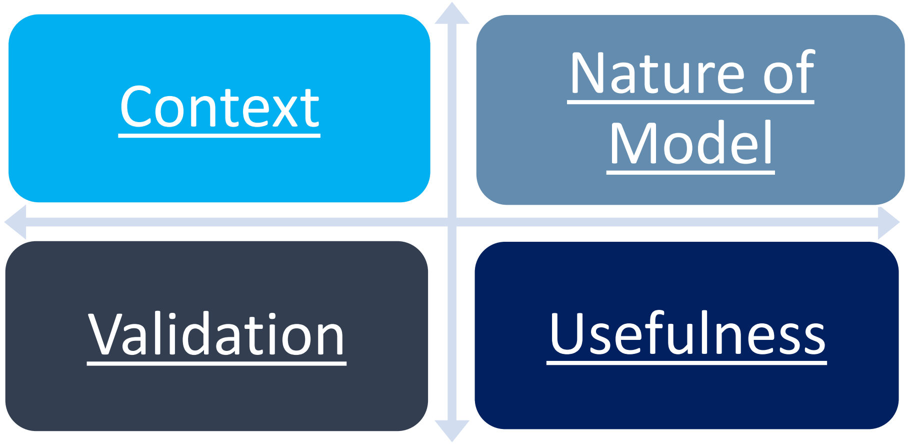
- What is an Energy System?

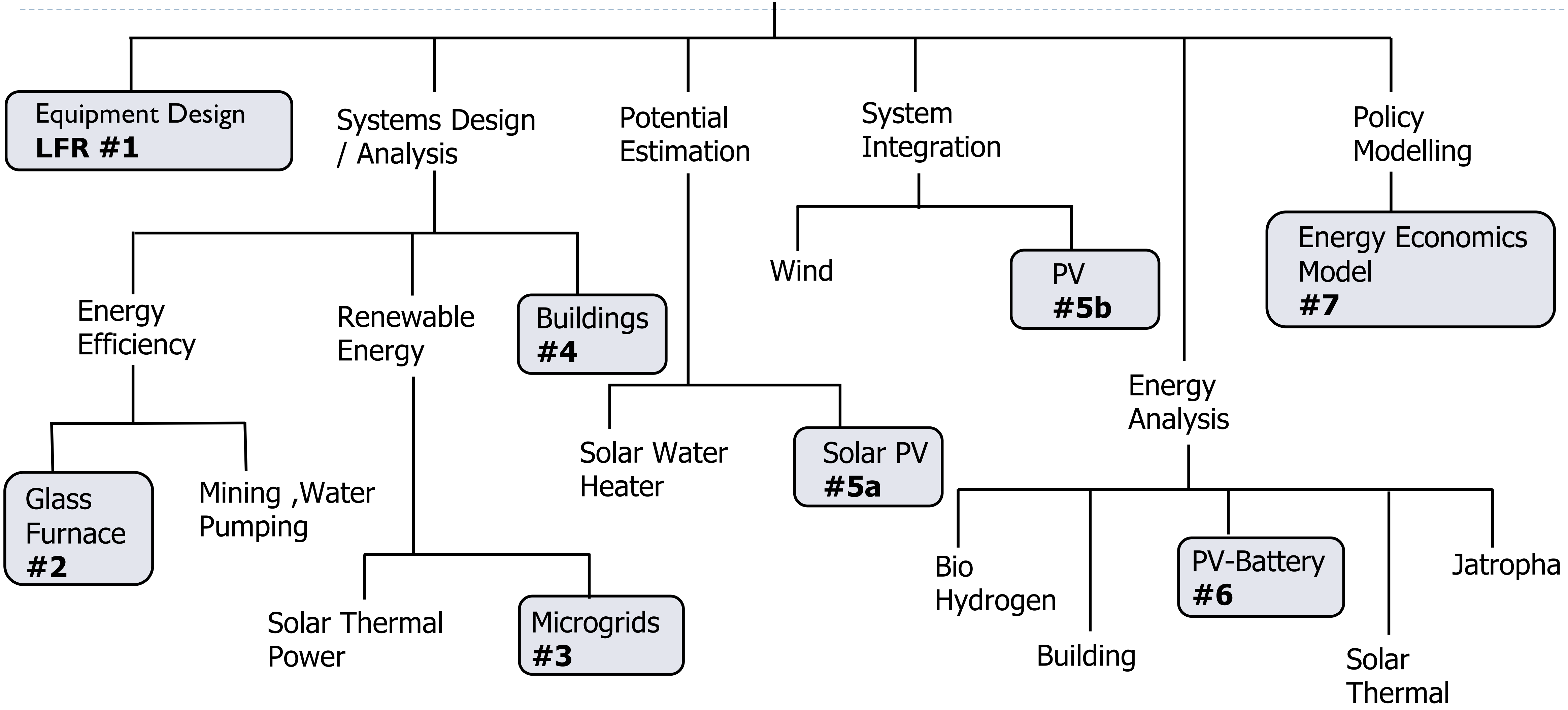
- Why model Energy Systems?

Steps in Model Development



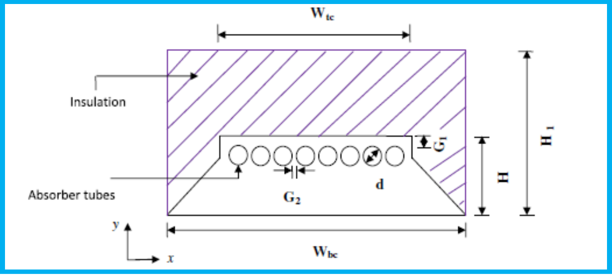


Energy Systems Modelling



Context

- Heat Losses Trapezoidal Cavity Linear Fresnel Reflector (LFR)

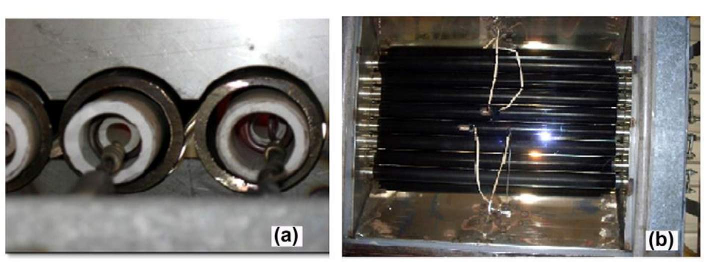


Nature of Model

- Two Dimensional- Mass, momentum, energy balances
- Fluent

Validation

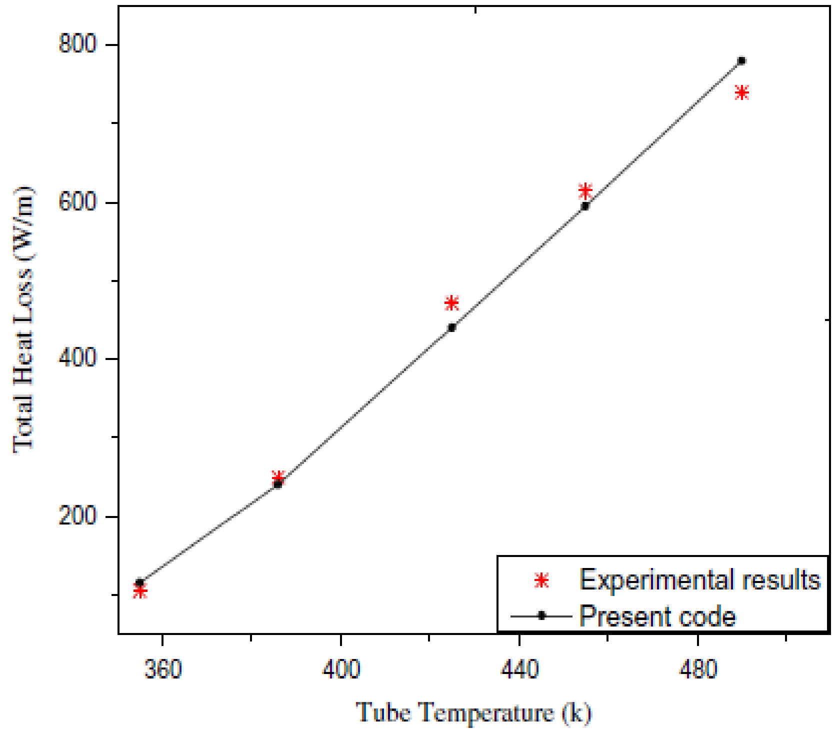
- Experimental setup, electric Heating, KG design



Usefulness

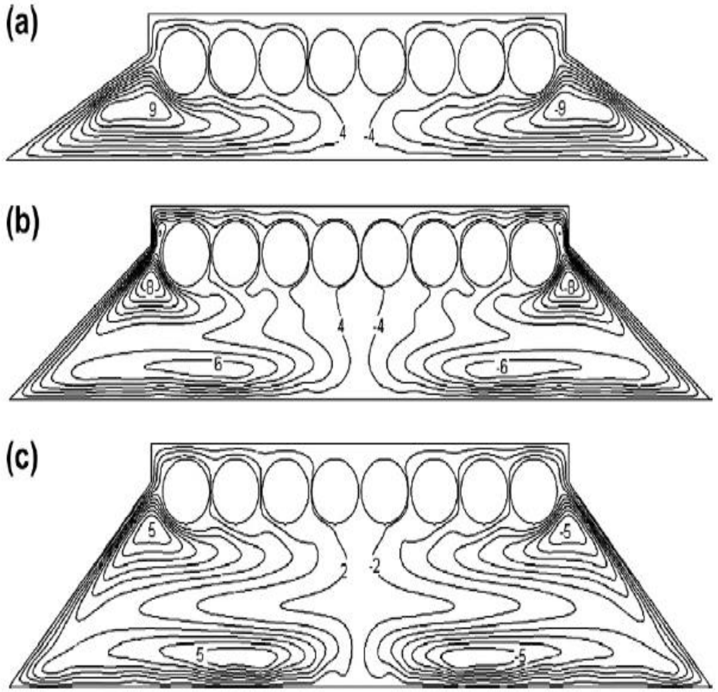
- Improved understanding of heat losses from LFR cavities
- Effect of variation of design parameters

$$\overline{Nu_t} = 0.084 Ra_d^{0.19} (T^*)^{0.53} \left(\frac{1}{H^*}\right)^{0.095} (1+\varepsilon)^{2.292} \left(\frac{h_{ext} W_{bc}}{k_{air}}\right)^{0.0304} \quad (21)$$



Validation of heat loss

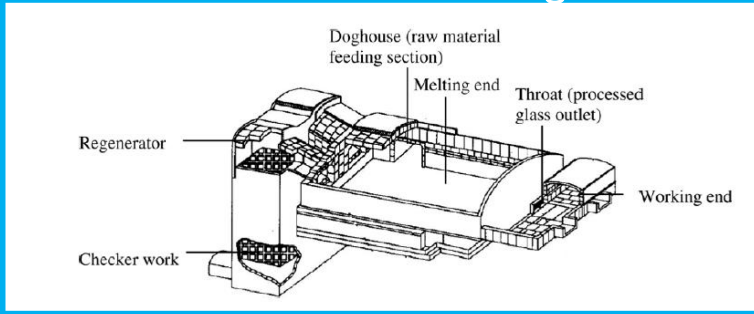
Sahoo et al, Renewable Energy, 2016



Effect of different height
H* = H/d
H* = a)2.25, b)3.0,c)3.75

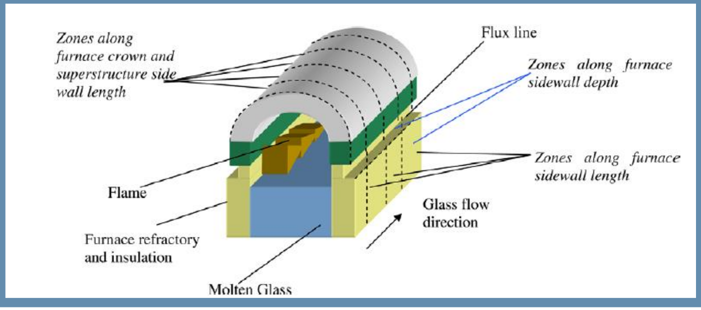
Context

- Industrial Glass furnace
- Model based benchmarking



Nature of Model

- Mass and Energy Balances –zones
- Heat loss correlations

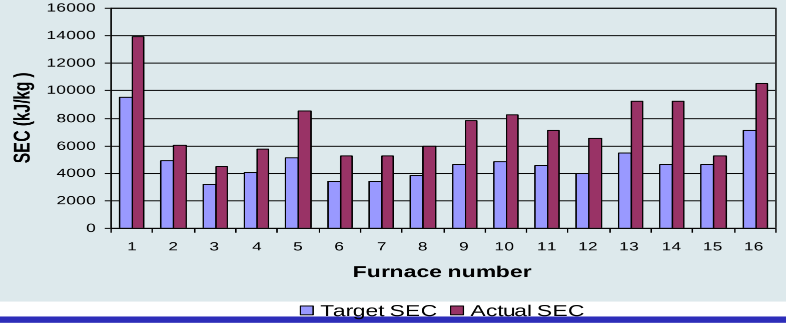


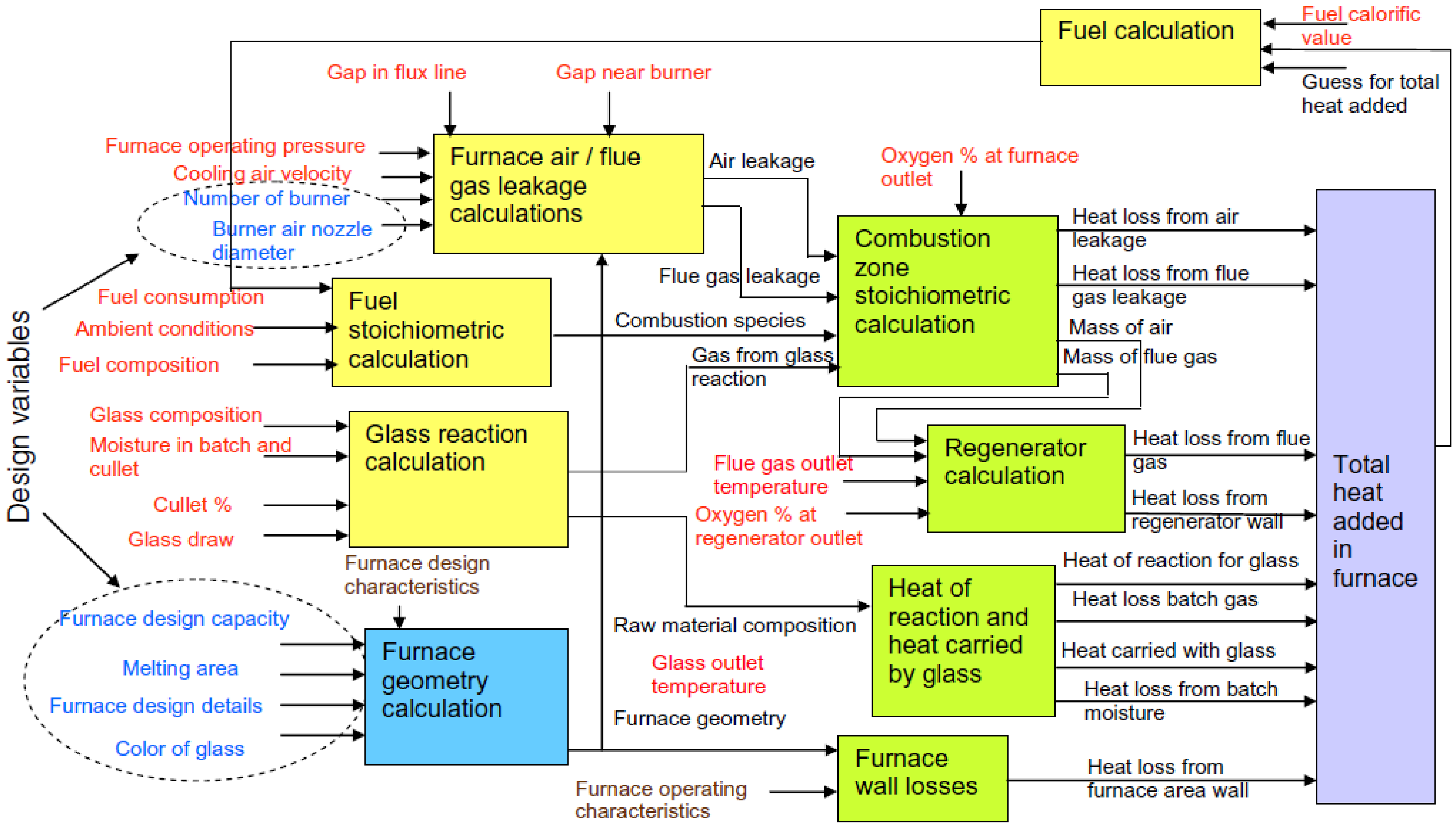
Validation

- Field Measurements, nine industrial glass furnaces
- Industry workshop

Usefulness

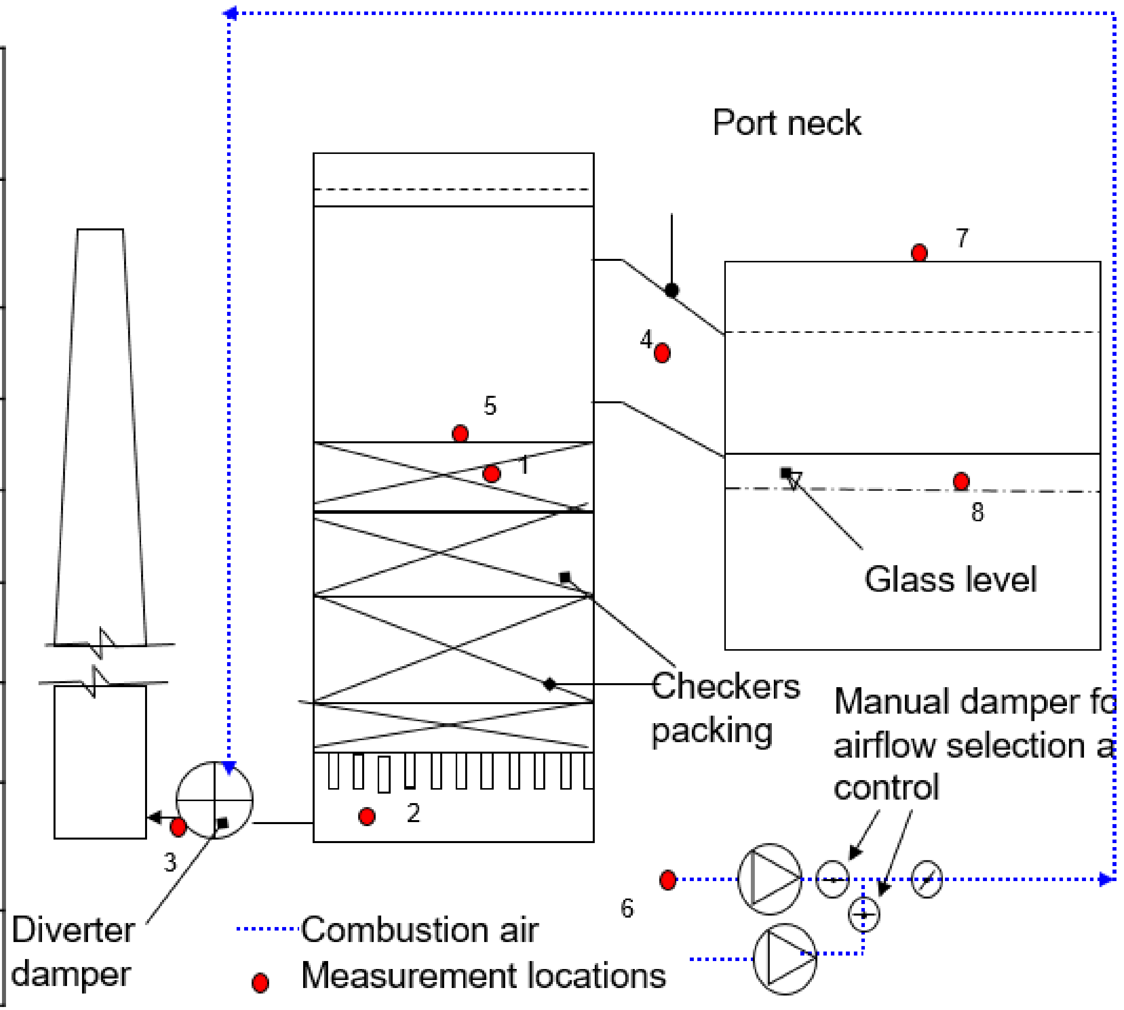
Target SEC – considering furnace characteristics



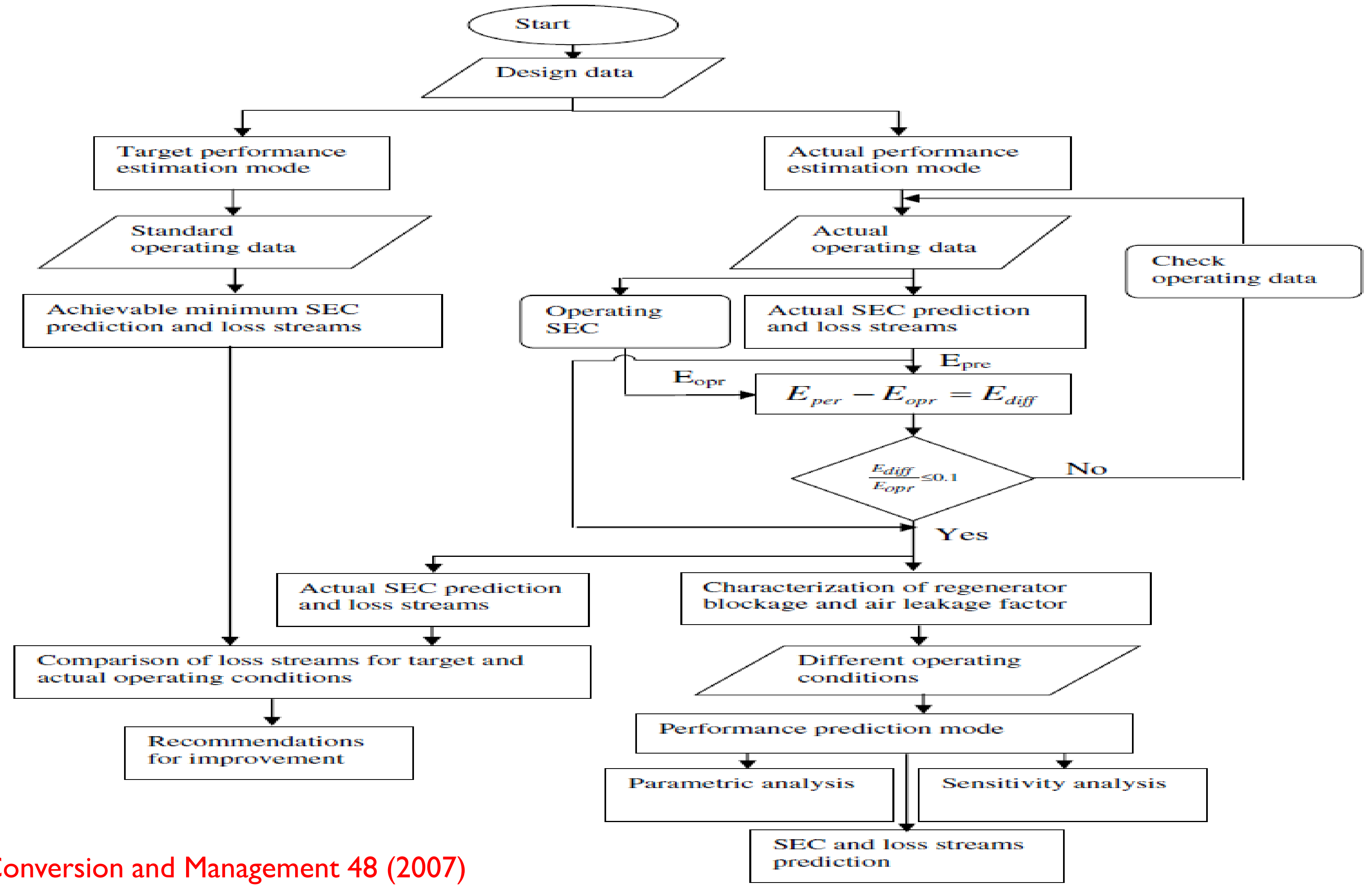


Vishal S. et al. Energy Conversion and Management 48 (2007)

Measurement location	Type of measurement
1	Oxygen % , Pyrometer checkers surface temperature
2	Oxygen %, Flue gas temperature
3	Oxygen %, Flue gas temperature
4	Oxygen %, Skin temperature
5	Pyrometer checkers surface temperature
6	Velocity of air at the suction of blower
7	Outside wall temperature for crown and side wall
8	Pyrometer glass surface temperature



V. Sardeshpande et al. Applied Energy 88 (2011)



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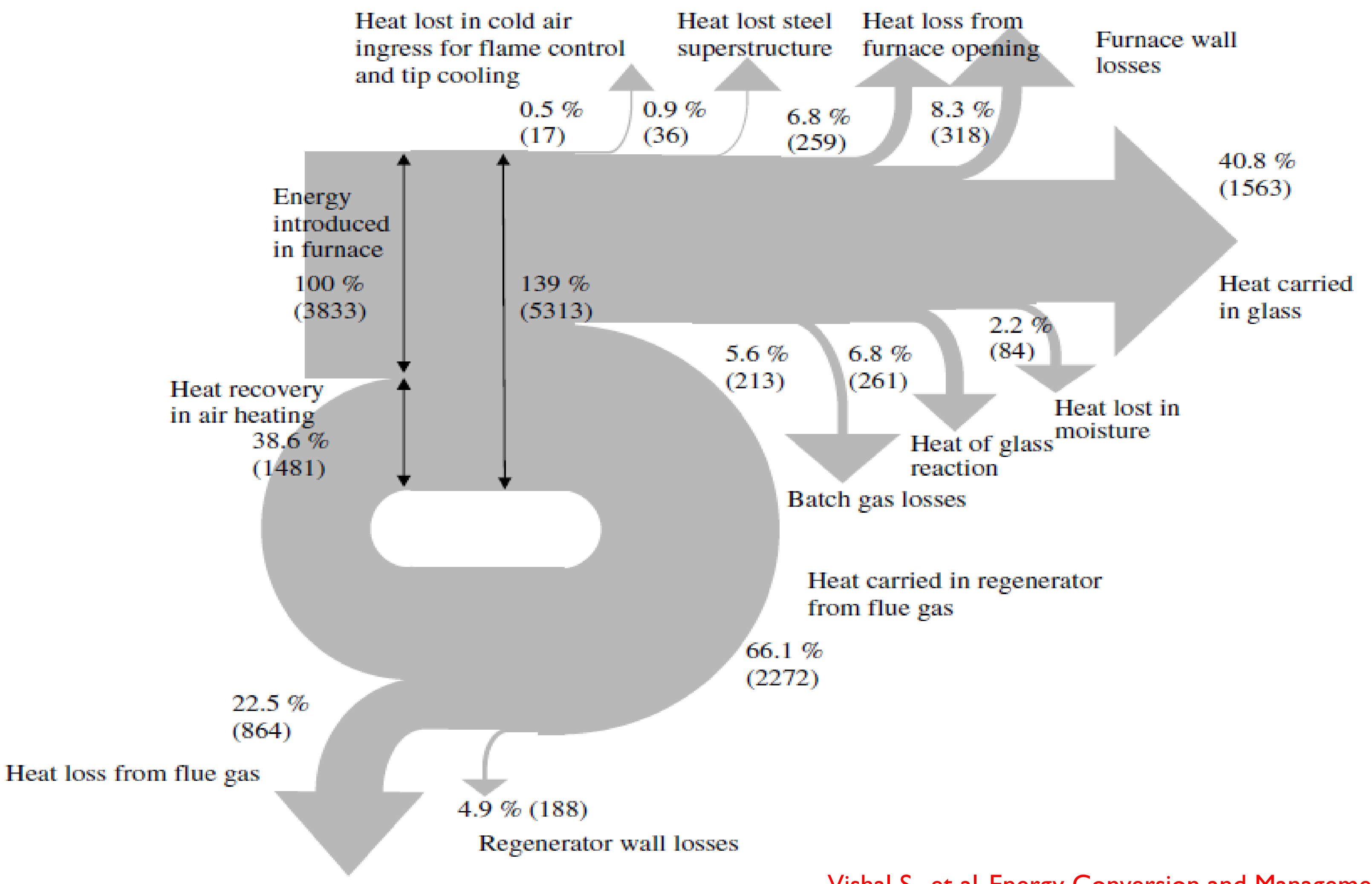


Vishal S. et al. Energy Conversion and Management 48 (2007)

Context

- Microgrid –isolated, grid support
- PV- battery- ultracapacitor- hydrogen storage
- Optimal sizing hybrid storage
- Supply, Demand variability

Nature of Model

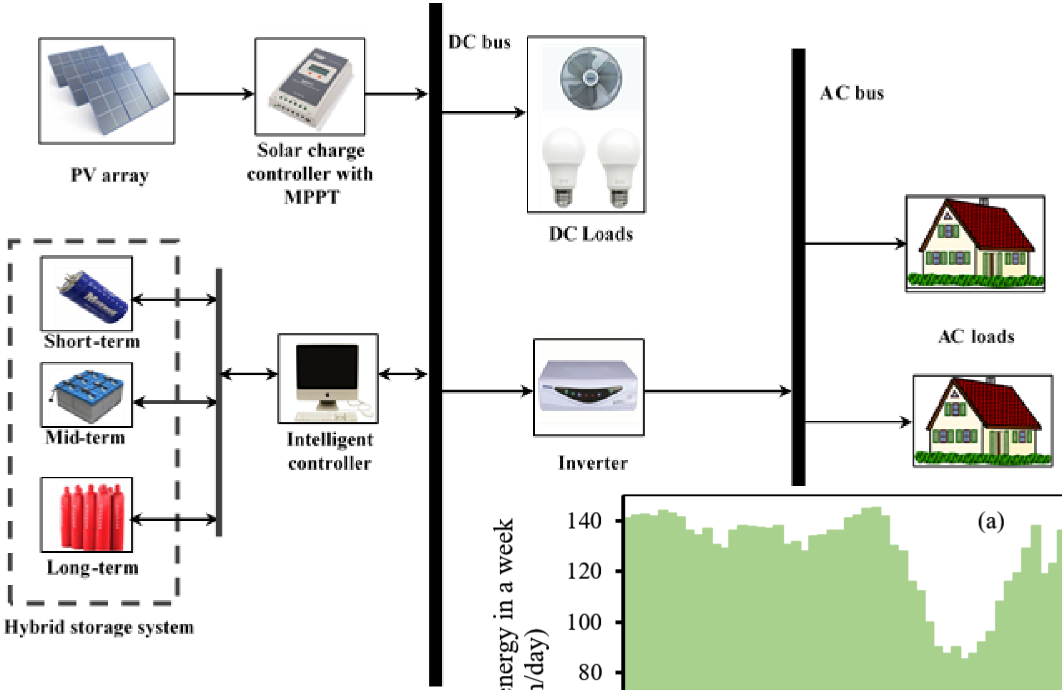
- Lumped parameter model for components
- Cumulative Energy supply and demand curves-Pinch , Design space approach
- Different time horizons
- Polymonial equations , Optimisation

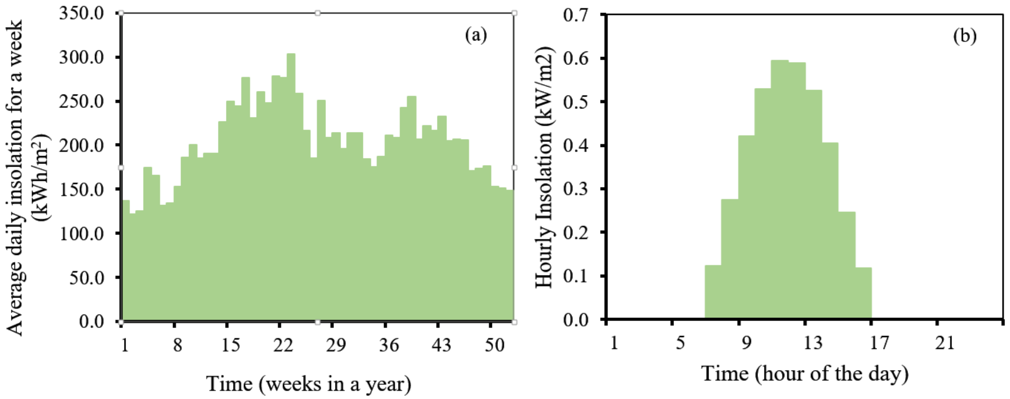
Validation

- Data logging for load variation – lift, welding loads
- Characteristics of components – manufacturers catalog
- Comparison with detailed simulation

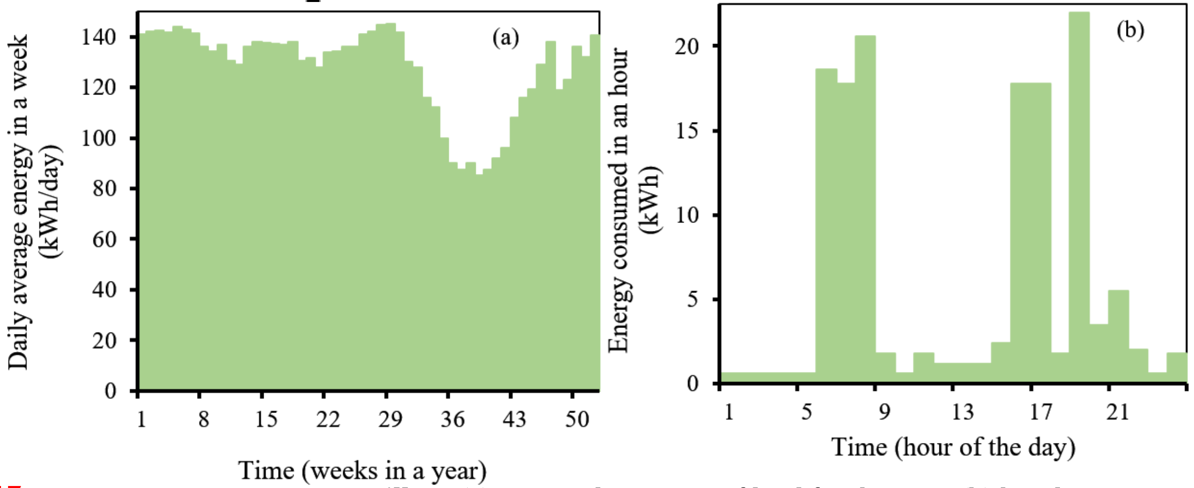
Usefulness

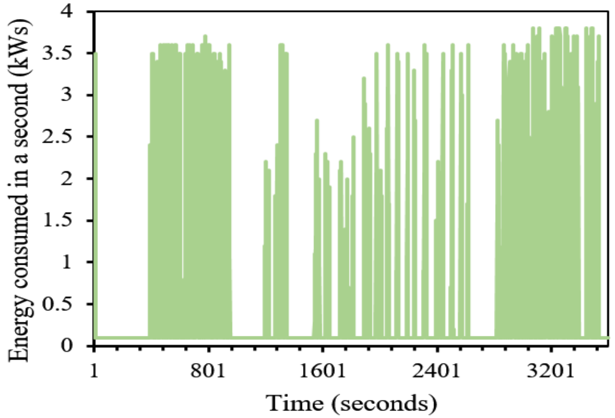
- Identification of feasible regions – design space
- Based on cost – can obtain minimum cost hybrid solutions





Insolation at New Delhi: (a) weekly average annual data and (b) hourly average daily data for a winter day





For a remote **welding shop** instantaneous variation in load for an hour

Jacob et al., Applied Energy, 2017

For a **remote village** (a) Seasonal variation of load for the year, (b) hourly variation of load

- Rate of Energy stored in storage device,
  - $\frac{dQ_s}{dt} = (P(t) - D(t))\eta_{stored}$ *P(t) – Source Power, D(t) – Load Power*

  Or $Q_s(t + \Delta t) = Q_s(t) + \int_t^{t+\Delta t}(P(t) - D(t))\eta_{stored}$

- For a very small time interval 'Δt'

$$Q_s(t + \Delta t) = Q_s(t) + (P(t) - D(t))\eta_{stored}$$

- Constraints

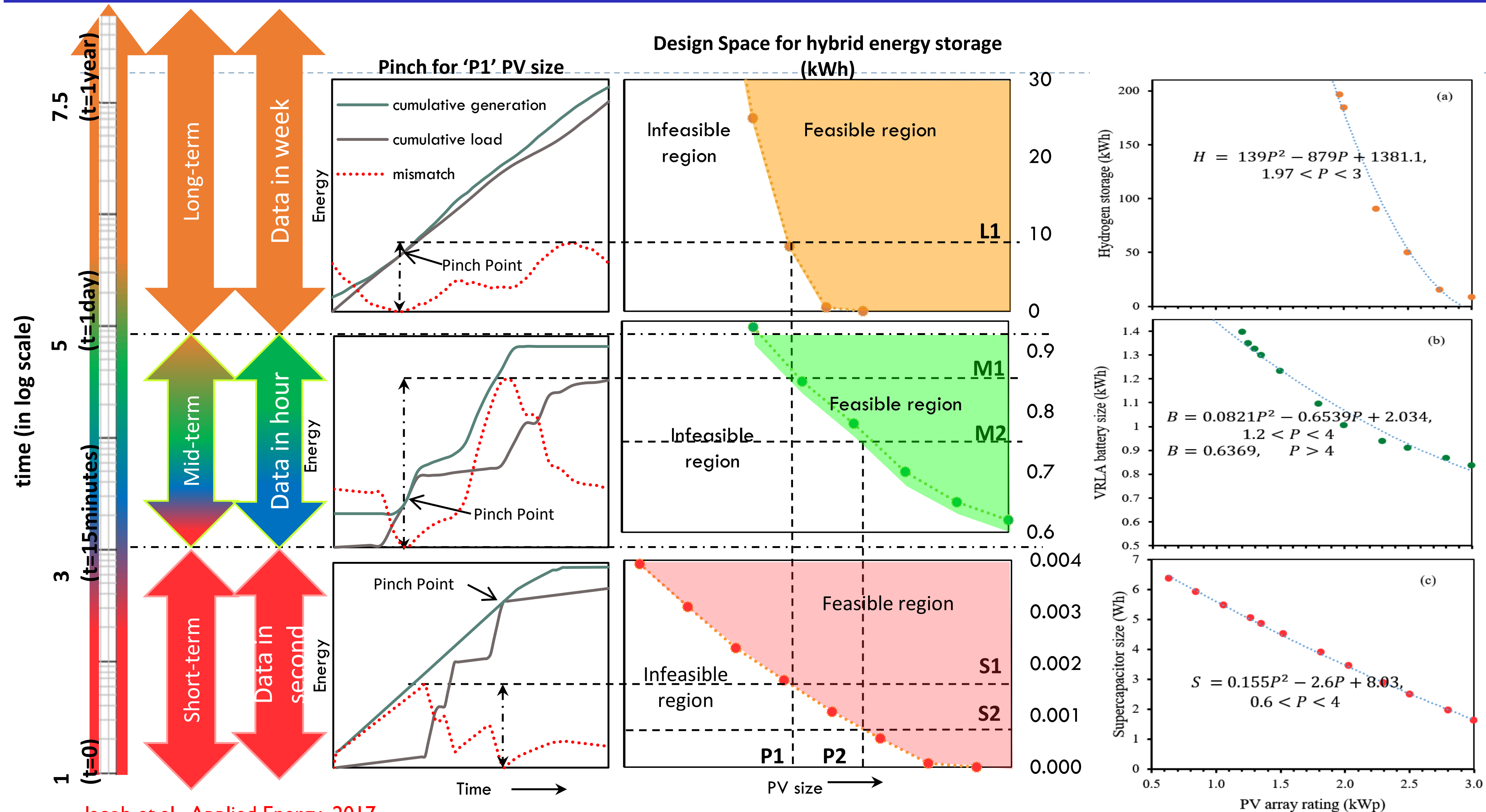
1)For the entire time horizon, T   Qs(t=0) = Qs (t=T)

2) Storage charge level Qs(t)≥0 for all time values

3) Generation should not exceed maximum power

$$Minimum\ Storage\ Capacity = \frac{\max(Q_s)}{DoD}$$

Jacob et al., Applied Energy, 2017



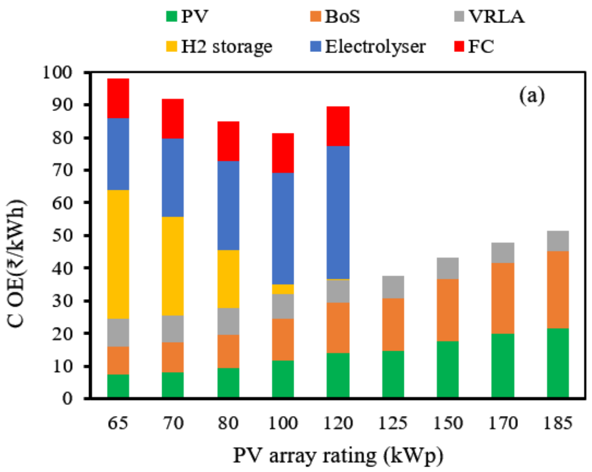
Jacob et al., Applied Energy, 2017

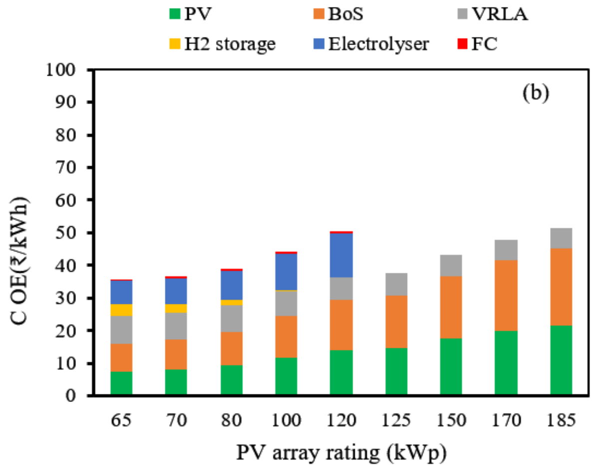
Quadratic fitting for the boundary points of the design space of stand-alone welding shop

(a) Hydrogen storage,

(b) VRLA battery

(c) Supercapacitor





COE (₹/kWh) for the different configurations of remote rural village case study (a) using present cost (b) using US DOE target cost for hydrogen storage

Case Study	Optimum Configuration						COE (₹/kWh)
	PV (kW_p)	Fuel Cell (kW)	Electrolyser (kW)	Hydrogen tank (m^3)	VRLA battery (kWh)	Supercapacitor (Wh)	
Case 1 – Rural Village	65	12	65	12.3	165	-	35
Case 2 – Telecom tower	40	6	40	5.2	58	-	33
Case 3 – Welding Shop	2	0.32	2	0.27	0.78	3.5	24
Case 4 – Backup for lift	1	-	-	-	2.7	69	30

Jacob et al., Applied Energy, 2017

Context

- Direct coupling of Optimisation algorithm with simulation computationally intensive for Building design
- Three storey building in Delhi

Nature of Model

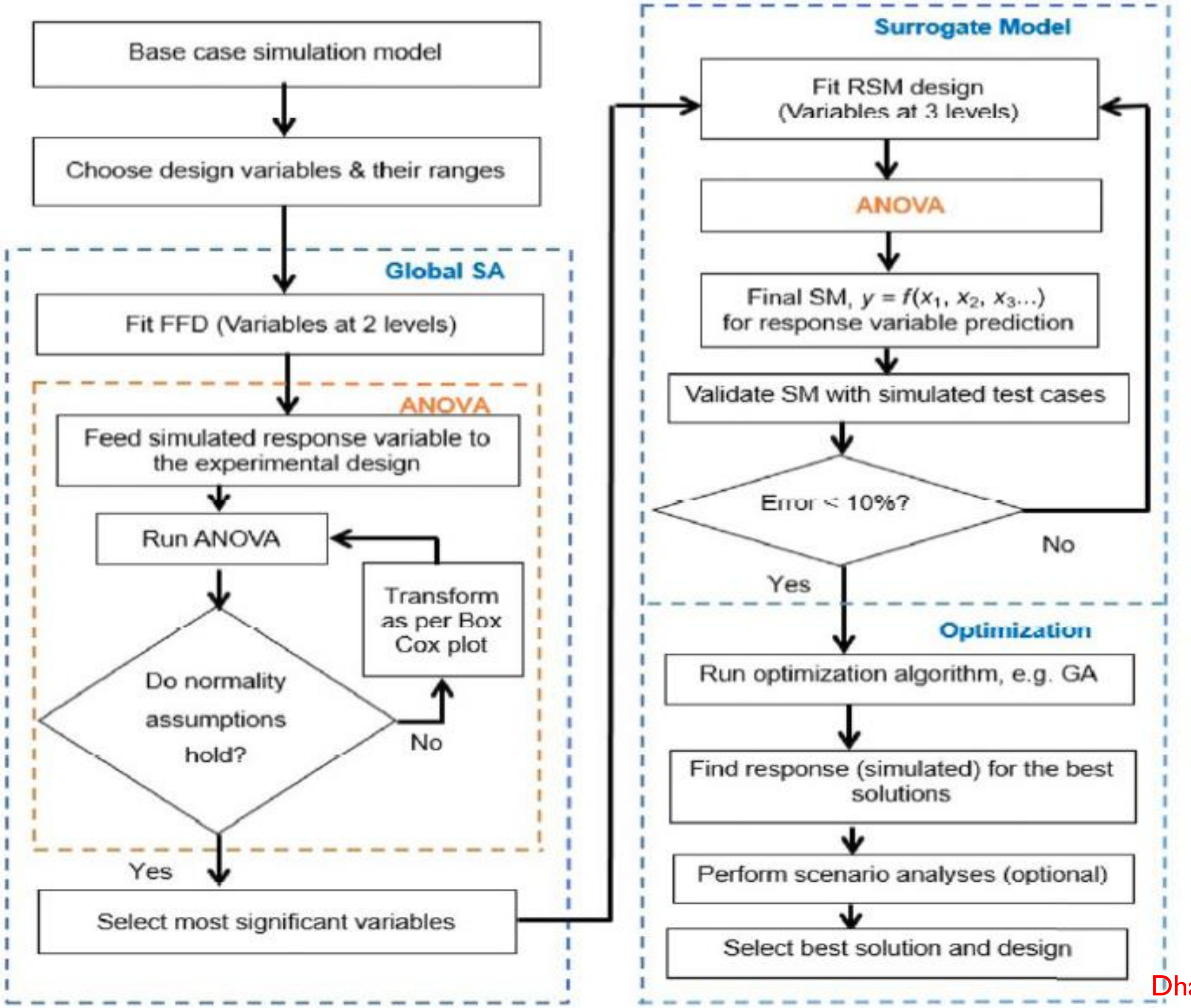
- Surrogate Models to approximate simulation
- Experimental Design (Fractional Factorial Design, Response Surface Methodology)
- Annual Cooling, Lighting Energy
- Optimisation- Genetic Algorithms

Validation

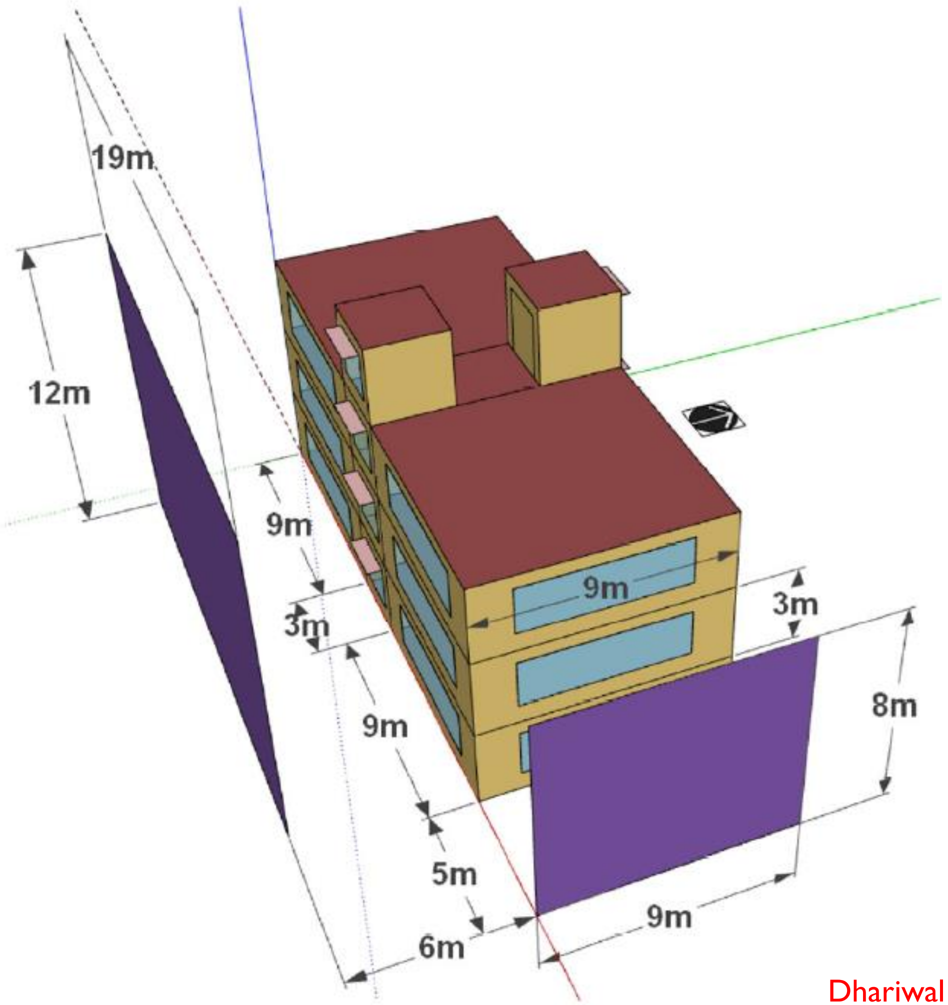
- Energy Plus used for validation
- Error less than 10%
- Used for 3-storeyed house in Delhi
- Team Shunya

Usefulness

- Methodology- reduces computational time, enables optimisation



Dhariwal and Banerjee, Building Simulation, Springer Nature (2017)



Design variable	Range
WWR	15% to 75%, 15% to 50%, 15% to 50%, 15% to 40%*
Window SHGC	0.2 to 0.8 for each facade*
Window VLT	0.2 to 0.8 for each facade*
Overhang depth	0 to 1 m for each facade*
Fin depth	0 to 1 m for each facade*
Window *U*-value	1 to 5.8 $W/(m^2 \cdot K)$
Roof reflectivity (ρ)	0.25 to 0.85
Wall insulation thickness (t)	0–0.1 m
Roof insulation thickness (t)	0–0.2 m
Wall additional thermal mass thickness (t)	0–0.1 m
Roof additional thermal mass thickness (t)	0–0.2 m

*North (N), east (E), west (W), south (S) facades respectively.

Dhariwal and Banerjee, Building Simulation, Springer Nature (2017)

$$\text{Zone 1 cooling capacity (in W)} = 634 \times CE_{\text{zone1}} + 749 \qquad (9)$$

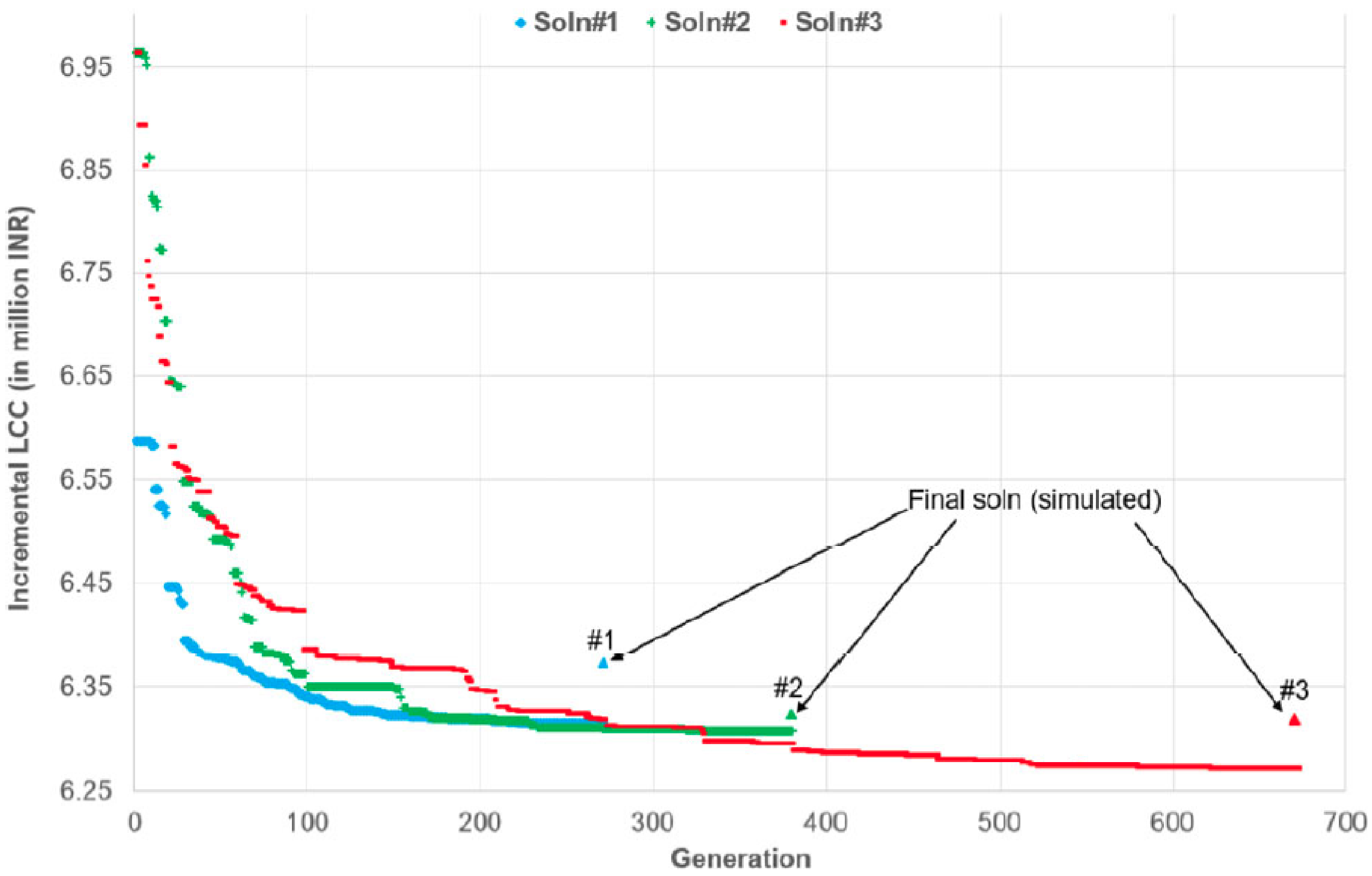
$$\text{Zone 2 cooling capacity (in W)} = 603 \times CE_{\text{zone2}} - 3264 \qquad (10)$$

$$\text{Zone 3 cooling capacity (in W)} = 495 \times CE_{\text{zone3}} + 84 \qquad (11)$$

$$\text{SHGC} = -0.16 + 0.65 \times \text{VLT} + 0.13 \times (\text{Window } U\text{-value}) - 0.01 \times (\text{Window } U\text{-value})^2 \qquad (12)$$

$$\frac{\text{WWR-N} + \text{WWR-E} + \text{WWR-W} + \text{WWR-S}}{4} \geq 40\% \qquad (13)$$

Dhariwal and Banerjee, Building Simulation, Springer Nature (2017)



Dhariwal and Banerjee, Building Simulation, Springer Nature (2017)

Context

- Roof top PV potential in city
- Solar Mission – focus on land based large plants

Nature of Model

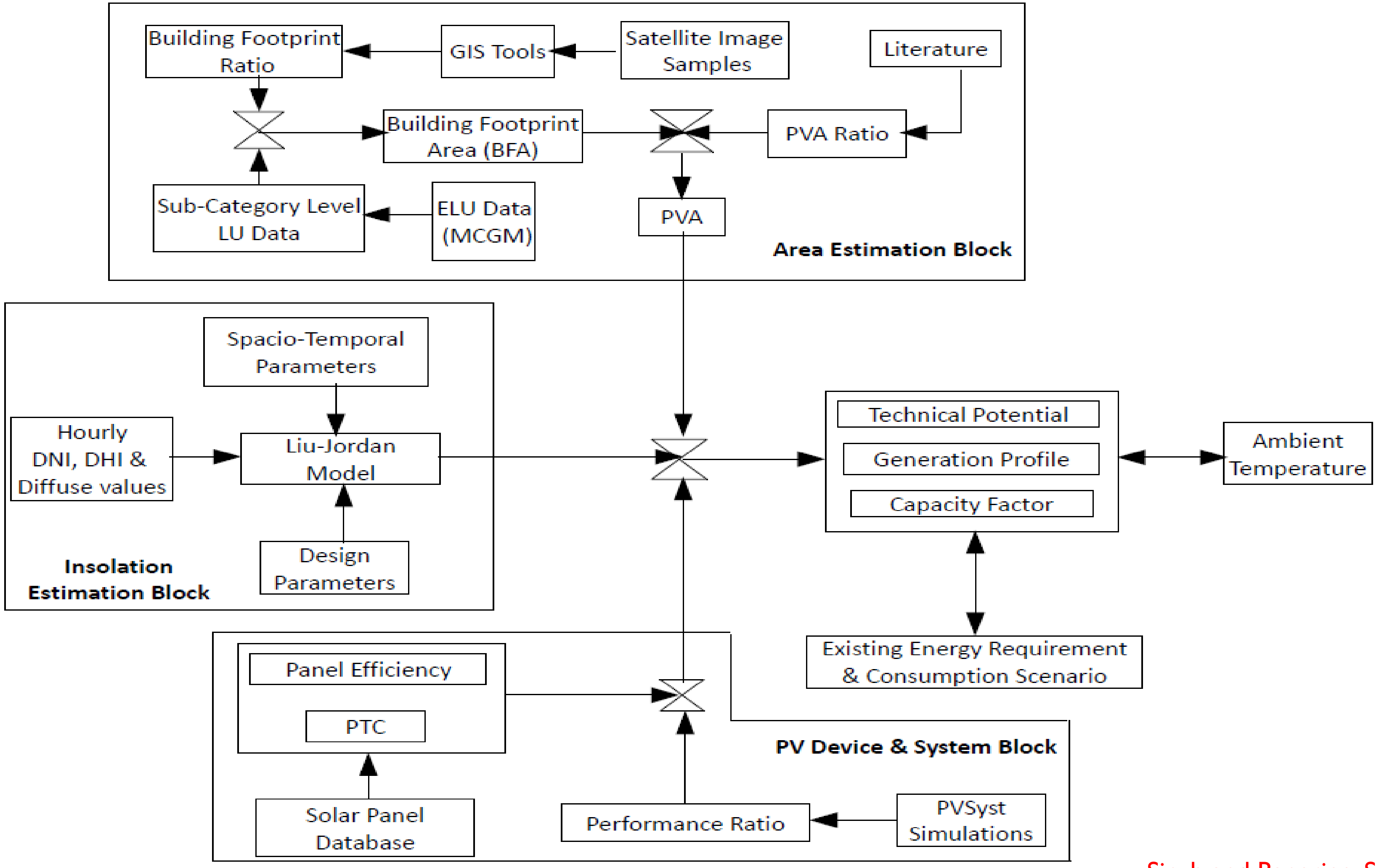
- Area Estimation,
- Insolation estimation,
- PV Device and System(PV Syst)
- Results and Analysis

Validation

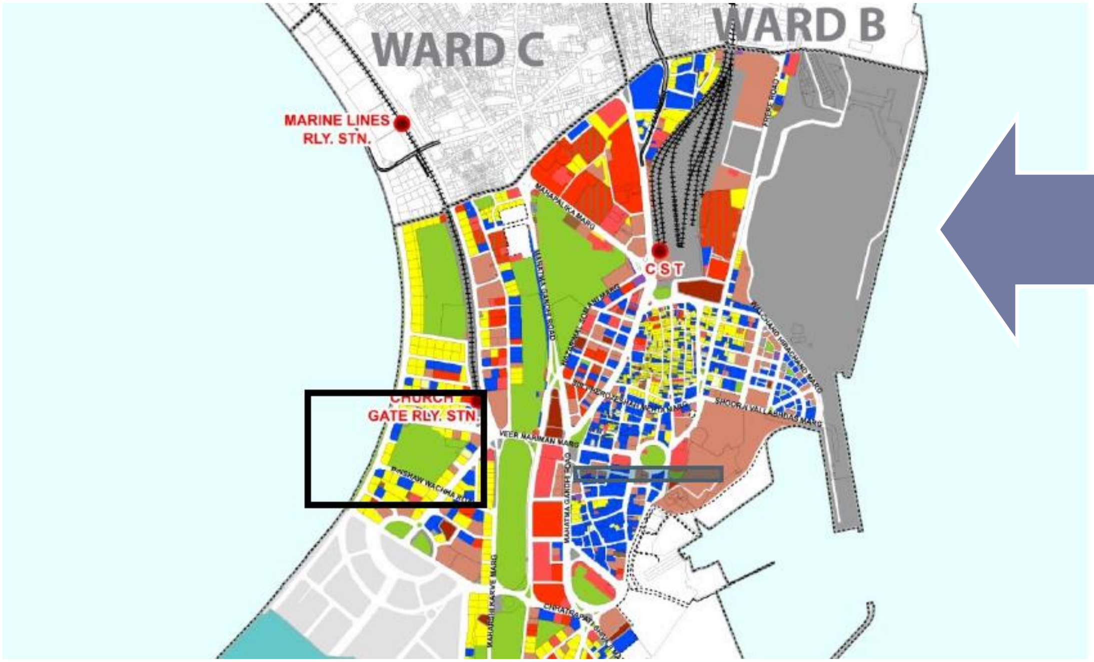
- Samples for land use types
- Comparison of PVA with literature

Usefulness

- Transparent Methodology
- Load profiles and PV generation-typical days – different months
- Applied for other cities – Bengaluru



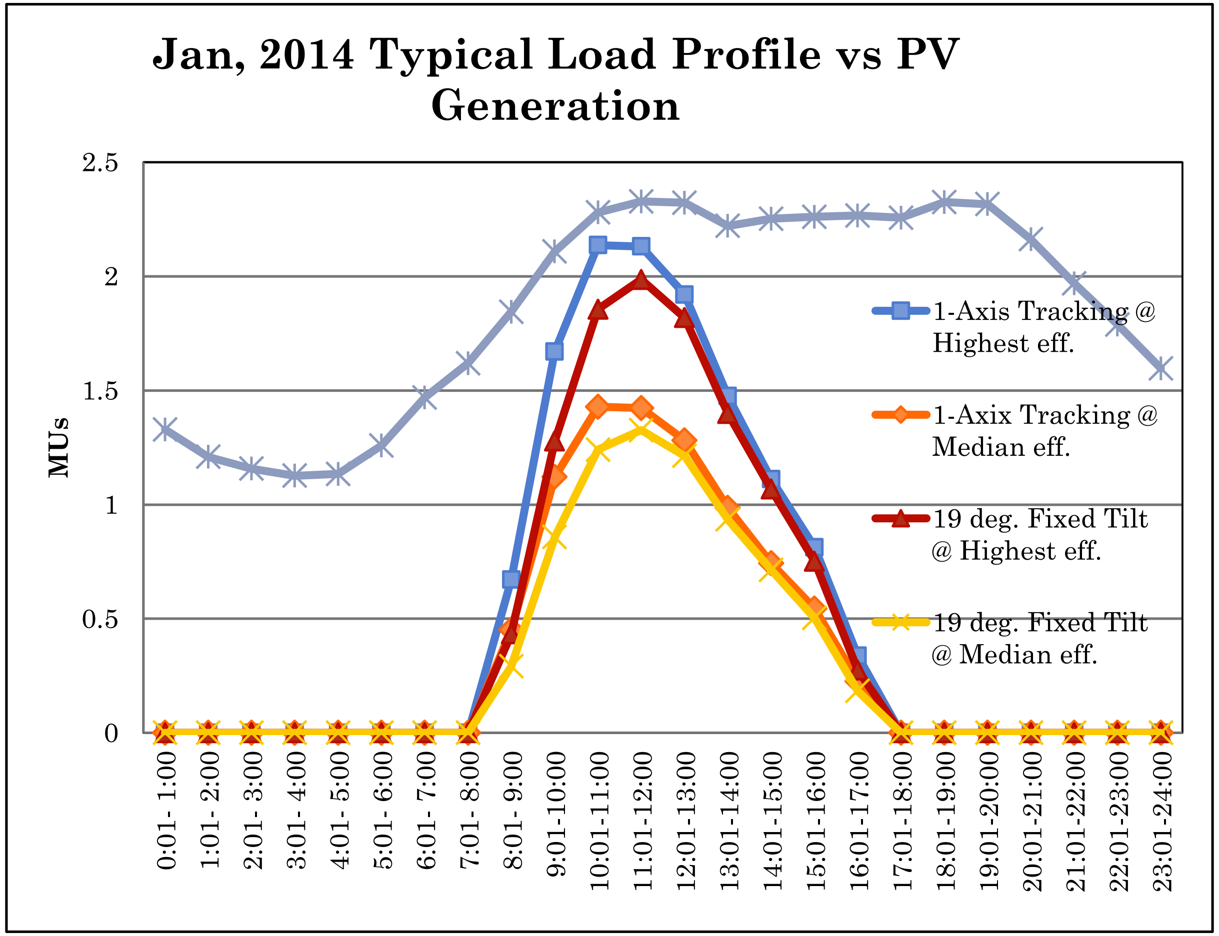
Singh and Banerjee, Solar Energy, 115, 2015

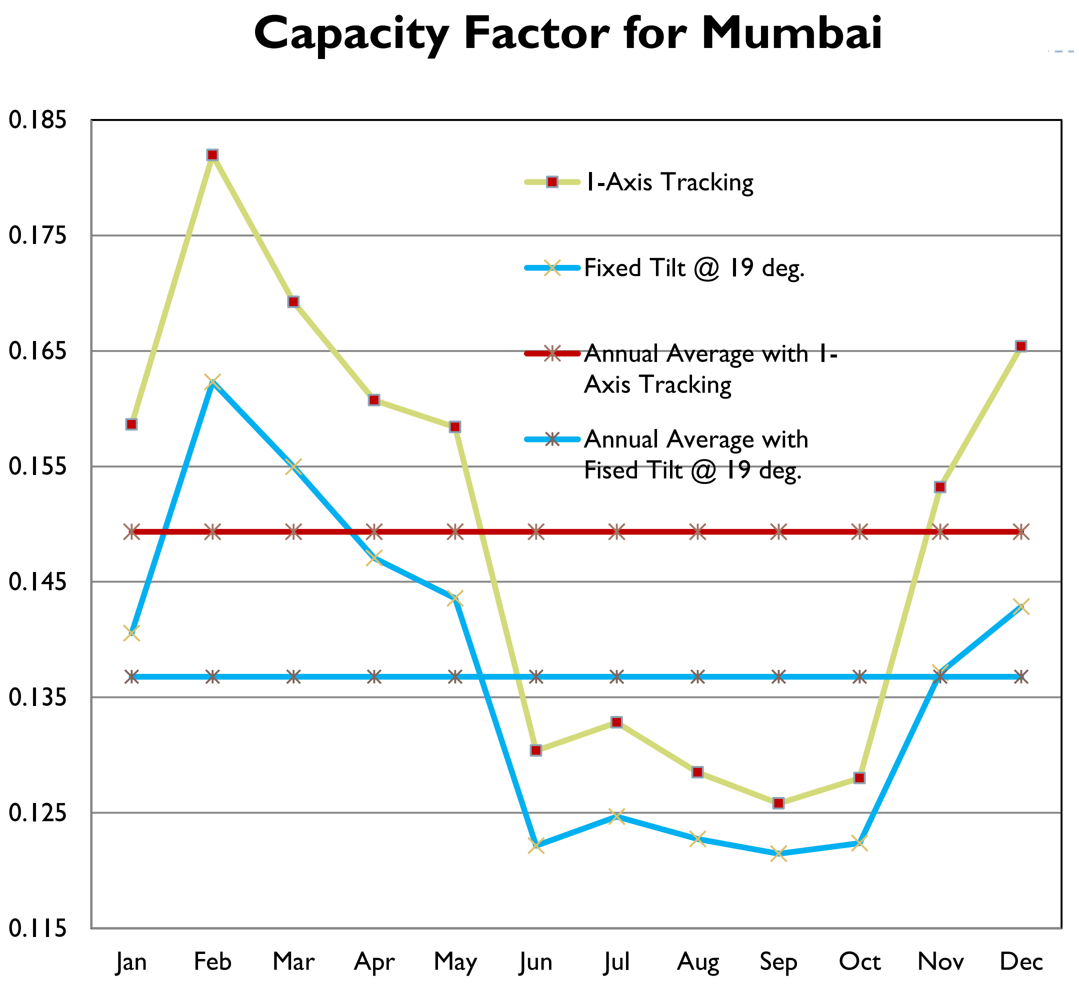


ELU map of Ward A of MCGM

Corresponding Satellite Imagery for the area from Google Earth

Singh and Banerjee, Solar Energy, 115, 2015


Jan, 2014 Typical Load Profile vs PV Generation
MUs
2.5
2
1.5
1
0.5
0
1-Axis Tracking @ Highest eff.
1-Axix Tracking @ Median eff.
19 deg. Fixed Tilt @ Highest eff.
19 deg. Fixed Tilt @ Median eff.
0:01- 1:00
1:01- 2:00
2:01- 3:00
3:01- 4:00
4:01- 5:00
5:01- 6:00
6:01- 7:00
7:01- 8:00
8:01- 9:00
9:01-10:00
10:01-11:00
11:01-12:00
12:01-13:00
13:01-14:00
14:01-15:00
15:01-16:00
16:01-17:00
17:01-18:00
18:01-19:00
19:01-20:00
20:01-21:00
21:01-22:00
22:01-23:00
23:01-24:00


Capacity Factor for Mumbai
0.185
0.175
0.165
0.155
0.145
0.135
0.125
0.115
1-Axis Tracking
Fixed Tilt @ 19 deg.
Annual Average with 1-Axis Tracking
Annual Average with Fised Tilt @ 19 deg.
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Context

- Conventionally Hydro Thermal scheduling problem
- Increased PV and renewable share
- Impact on grid ?

Nature of Model

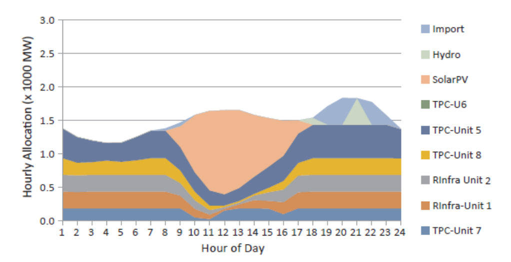
- PV must run
- Two stage formulation using dynamic programming and linear programming

Validation

- Proposed HTSS algorithm compared with stochastic algorithm in literature
- Savings of 8.2%
- Case study of Mumbai – actual data

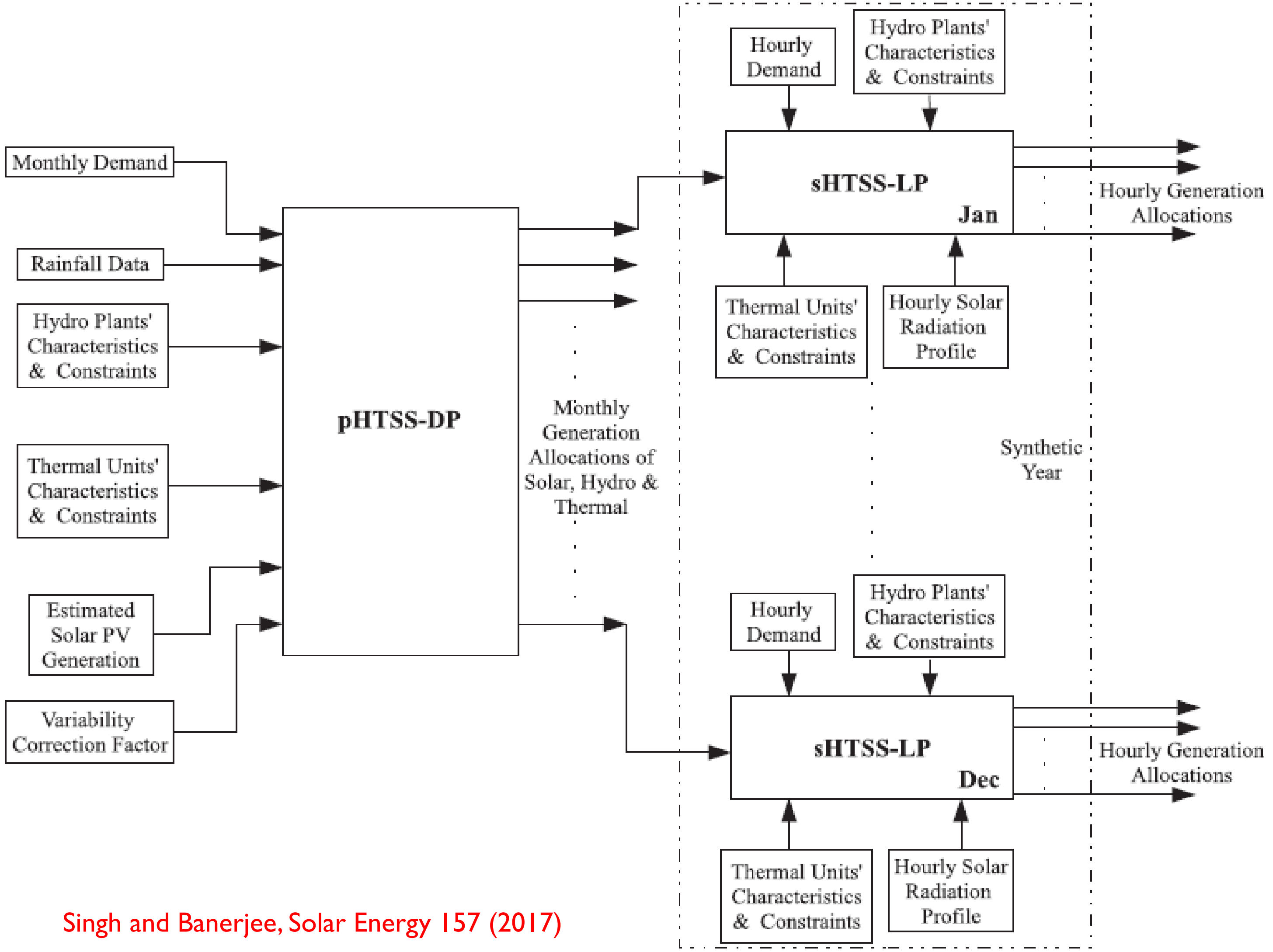
Usefulness

Impact on load profile for different PV penetration



(c) $\beta = 1.0$: sHTSS-LP result

Solar PV integration -Algorithm



Singh and Banerjee, Solar Energy 157 (2017)

Solar PV integration –Objective function

$$\underset{\hbar_h^{reg},\hbar_h^{hol},\theta_{h,i}^{reg},\theta_{h,i}^{hol}}{Minimize} \left[\begin{array}{l} d_{reg} \times \left(\sum_{i=1}^{n} (c_i \times \sum_{h=1}^{24} \theta_{h,i}^{reg}) + c_{imp} \times \sum_{h=1}^{24} (D_h^{reg} - (\hbar_h^{reg} + \beta \cdot E_h^{solar} \cdot CF_{var} + \sum_{i=1}^{n} \theta_{h,i}^{reg})) \right) + \\ d_{hol} \times \left(\sum_{i=1}^{n} (c_i \times \sum_{h=1}^{24} \theta_{h,i}^{hol}) + c_{imp} \times \sum_{h=1}^{24} (D_h^{hol} - (\hbar_h^{hol} + \beta \cdot E_h^{solar} \cdot CF_{var} + \sum_{i=1}^{n} \theta_{h,i}^{hol})) \right) \end{array} \right]$$

Singh and Banerjee, Solar Energy 157 (2017)

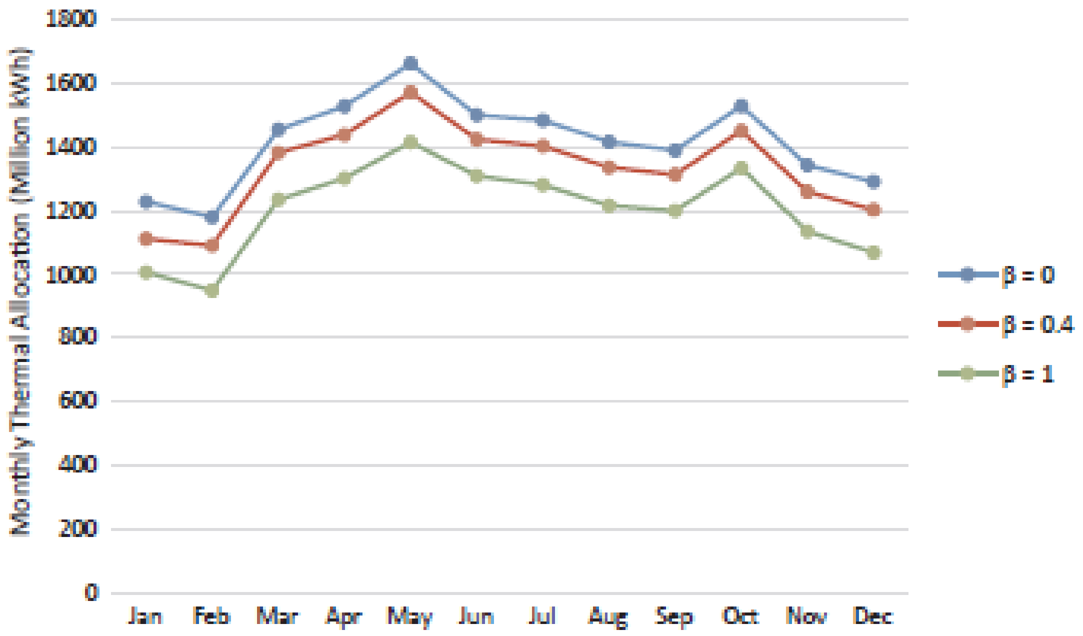
Input Data on hydro, thermal plants –Mumbai

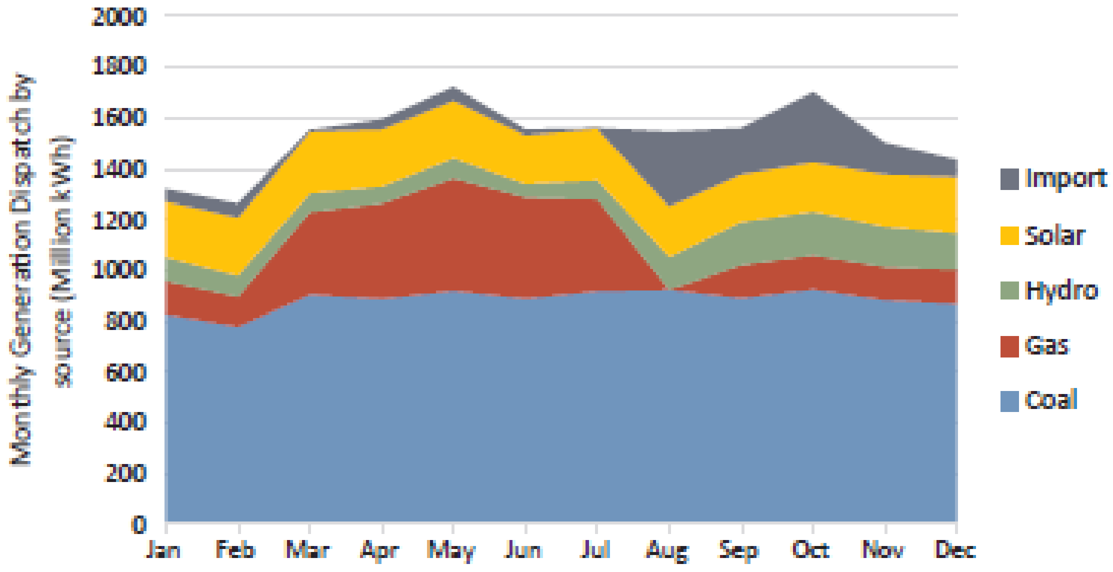
Priority List of Fossil-Fuel Based Generating Units for Mumbai.

S.No.	Unit name	Annual Average Energy Cost per Unit (INR/kWh)	Rated capacity (MW)	Fuel	Ramp rate (MW/min)
1	TPC-Unit 7	2.81	180	Gas	8–12
2	RInfra Unit 1	2.88	250	Coal	1–3
3	RInfra Unit 2	2.88	250	Coal	1–3
4	TPC-Unit 8	4.06	250	Coal	1–3
5	TPC-Unit 5	4.15	500	Coal	1–3
6	TPC-Unit 6	10.76	500	Gas	8–12
7	Grid Import	Variable	Varies	–	–
8	TPC-Unit 4	14.18	150	Oil	

Name of Hydro Unit	Khopoli	Bhivpuri	Bhira
Location	18.8°N, 73.4°E	18.9°N, 73.5°E	18.5°N, 73.4°E
Name of Main Reservoir	Walwan Lake	Andhra Lake	Mulshi Lake
Design Capacity (MWe)	72	75	300
Annual Design Energy (Million kWh)	293	339	1217
Capacity Factor (%)	46.45	51.6	46.31
Full Reservoir Level (m)	635.2	668	607.1
Minimum Draw Down Level (m)	619.4	646	590.1
Gross Storage Capacity (MCM)	72.5	363.7	747
V_1^D (m) (as in Eq. (6))	627.3	657	598.6

Singh and Banerjee, Solar Energy 157 (2017)





(c) β = 1.0

Case	Annual Generation-Cost Estimate from sHTSS-LP (Million INR)	% change from β = 0 case
β = 0	97,530	0
β = 0.2	91,449	−6.2
β = 0.4	85,469	−12.4
β = 0.6	79,672	−18.3
β = 0.8	74,313	−23.8
β = 1.0	69,610	−28.6

Singh and Banerjee, Solar Energy 157 (2017)

Context

- Microgrid scenarios for India-Urban, rural, industrial and isolated
Model based analysis of energy for a PV battery system

Nature of Model

- Direct energy requirements for the PV battery system for the designed microgrid

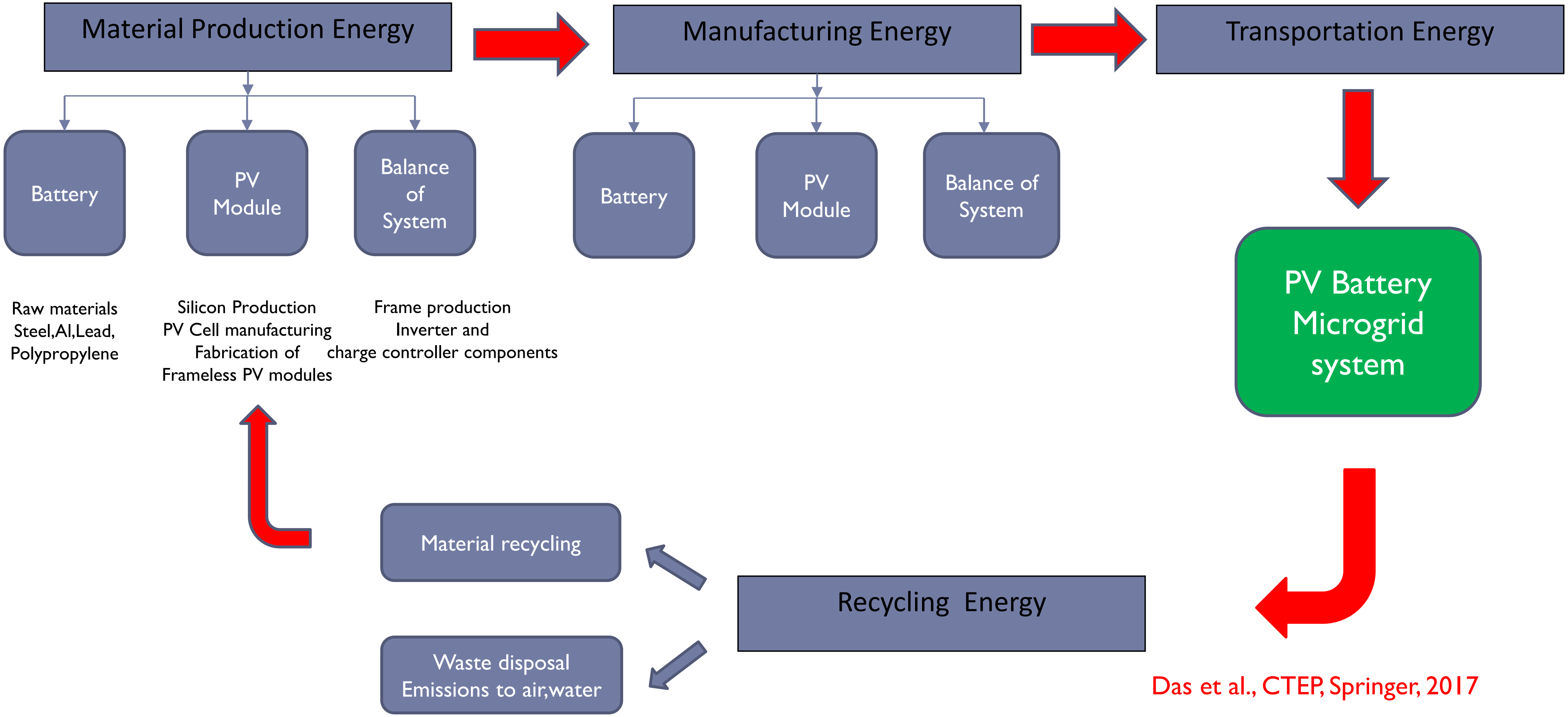
Validation

- Actual system components and their service life

Usefulness

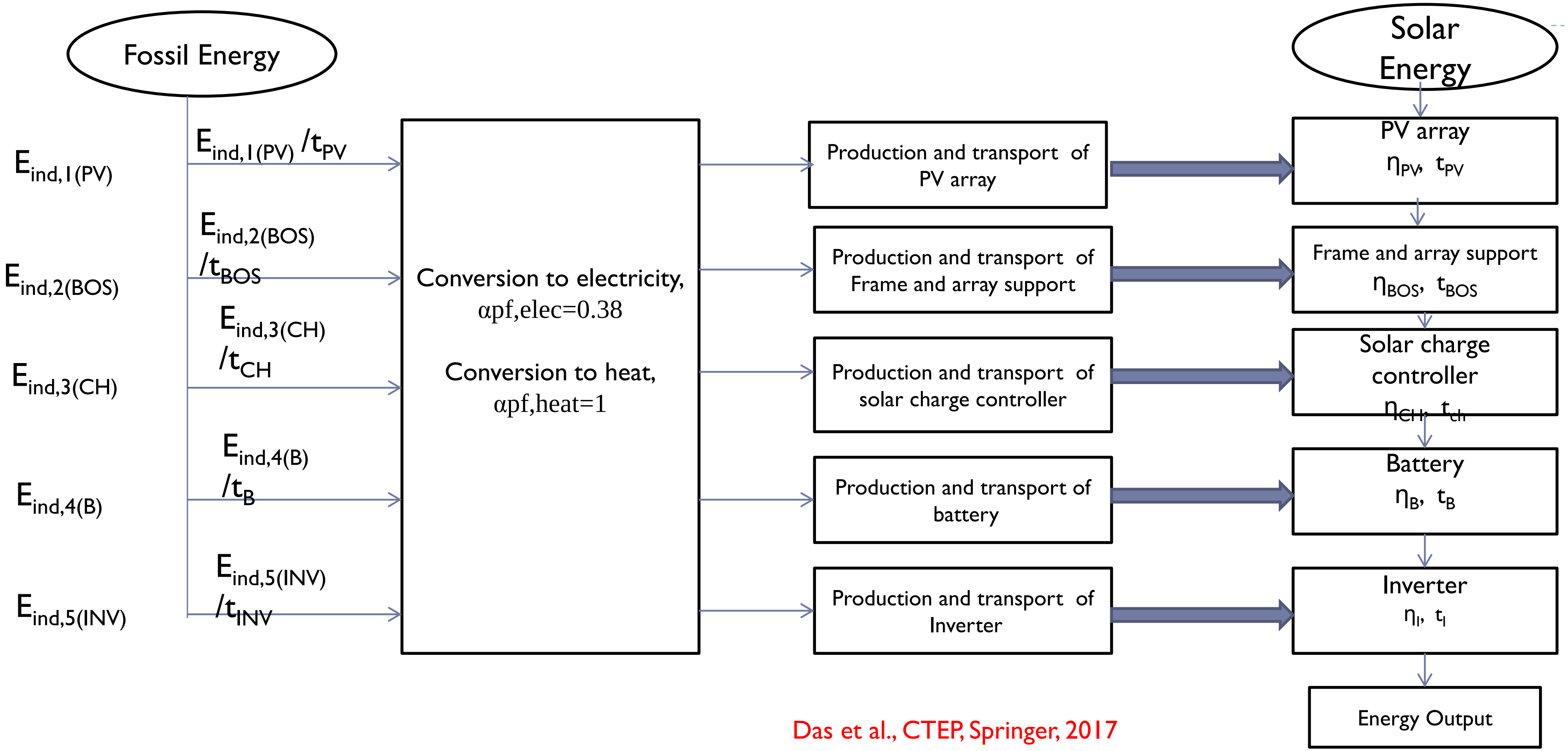
- Sustainability analysis
- Cradle to Gate
- Pay back time and net energy ratio
- Comparison of different options

Life Cycle Energy Analysis Flow diagram



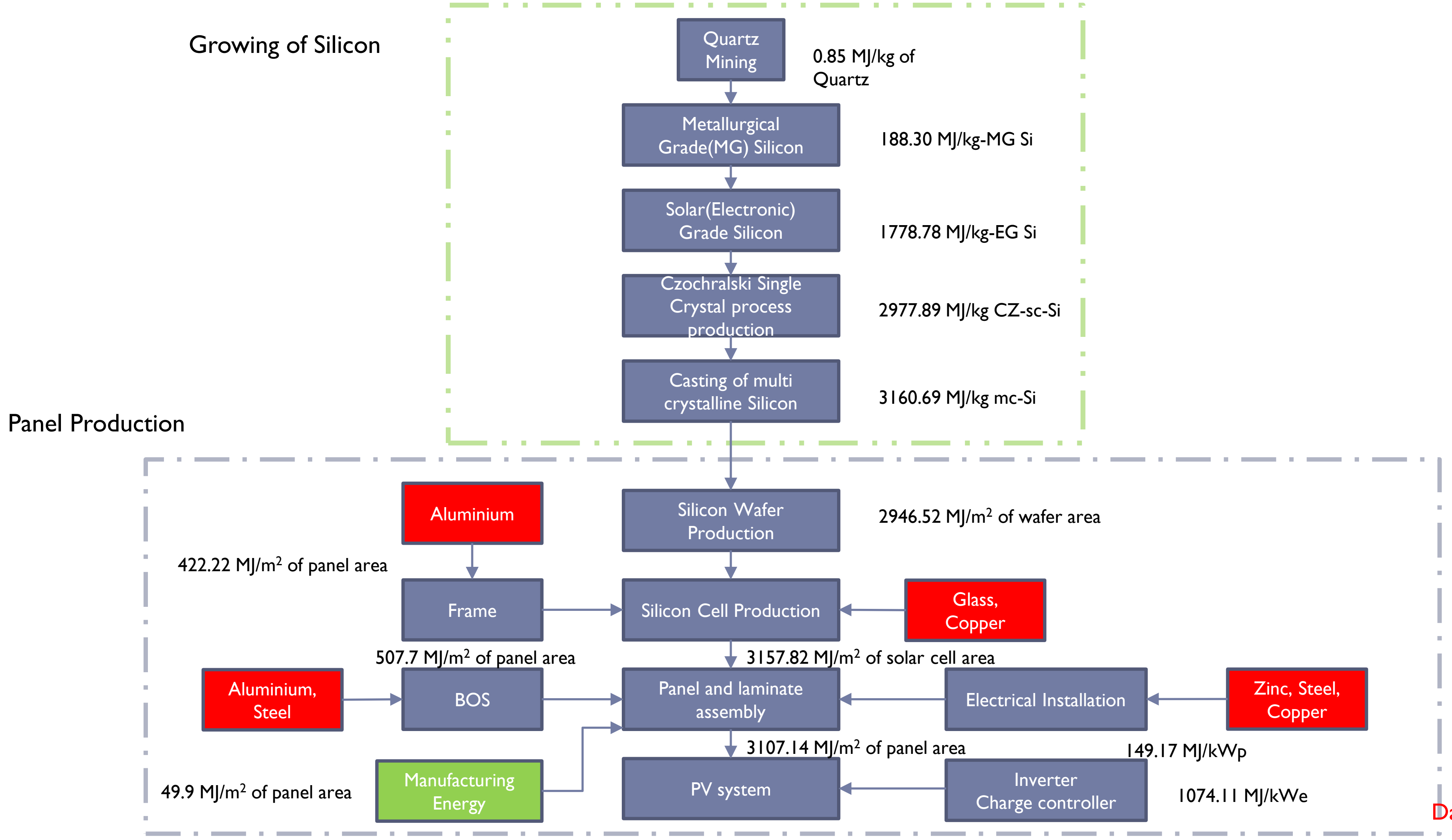
Das et al., CTEP, Springer, 2017

Energy flow diagram for PV battery system



Das et al., CTEP, Springer, 2017

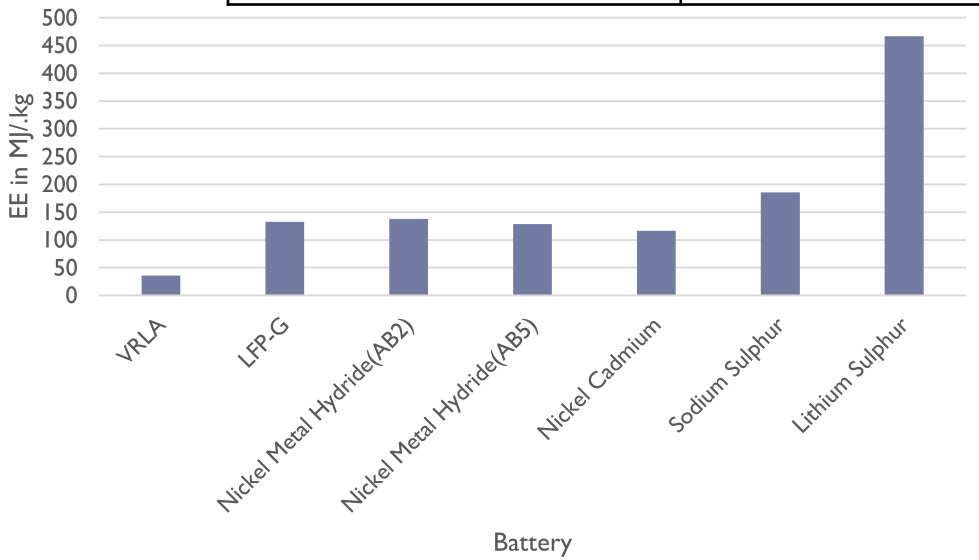
Energy Flow diagram of PV panel for India



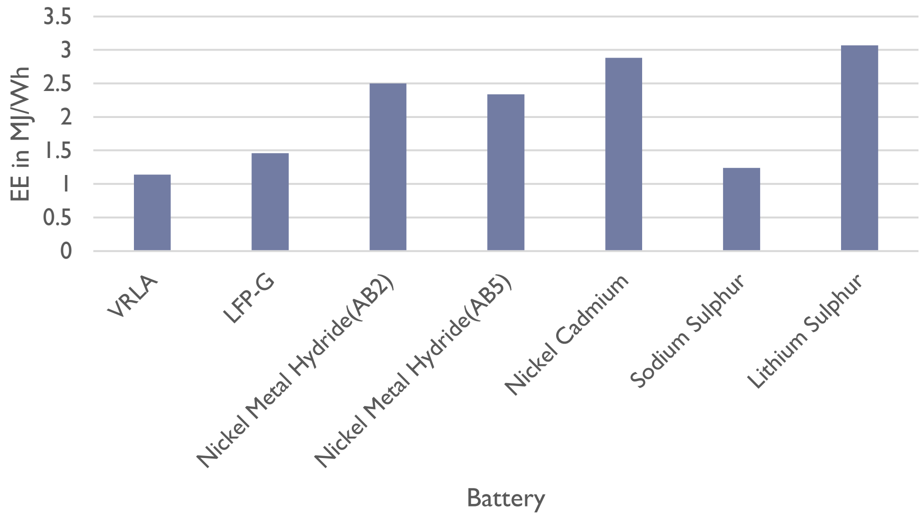
Das et al., CTEP, Springer, 2017

Energy Requirement of microgrid components

Component	Material Production Energy	Manufacturing Energy of PV panel, frame and BOS	Transportation Energy
PV system (multicrystalline-Silicon)	3107.14MJ_{pf}/m^2 of sensing area	49.9 MJ_{pf}/m^2 of panel area	0.34 MJ_{pf}/kg of panel weight
Frame	422.22 MJ_{pf}/m^2 of frame area		
Balance of System(BOS)	507.7 MJ_{pf}/m^2 of panel area		
Electrical Installation	149.17 MJ_{pf}/kWp		
Charge Controller	1074.11 MJ_{pf}/kWe		
Inverter	1074.11 MJ_{pf}/kWe		



Embodied Energy per unit mass for different batteries



Embodied Energy per unit storage capacity for different batteries

Das et al., CTEP, Springer, 2017

Indicators for different PV+ battery configurations

PV+battery configuration	Energy Pay Back Time(years)	Net Energy Ratio	Energy Pay back (% of cycle life)	Emission Factor ($kgCO_2$/kWh of output)
VRLA	2.75	4.63	20.10	0.26
LFP-G	2.62	6.55	6.88	0.14
NiMH(AB_2)	3.44	2.52	36.92	0.42
NiMH(AB_5)	3.4	2.63	34.12	0.42
NaS	4.3	3.9	7.58	0.67
NiCd	2.69	4.2	64.12	0.091
LiS	3.38	2.8	67.56	0.31

$$\text{EPBT} = \frac{\text{LifeTime Energy Input to the system}}{\text{Annual Energy Output}}$$

$$\text{NER} = \frac{\text{Annualised energy output}}{\text{Annualised energy input}}$$

Das et al., CTEP, Springer, 2017

Context

- Modelling framework to link Energy, Economy, Environment – not adequate
- Impact of structure of economy, climate constraint

Nature of Model

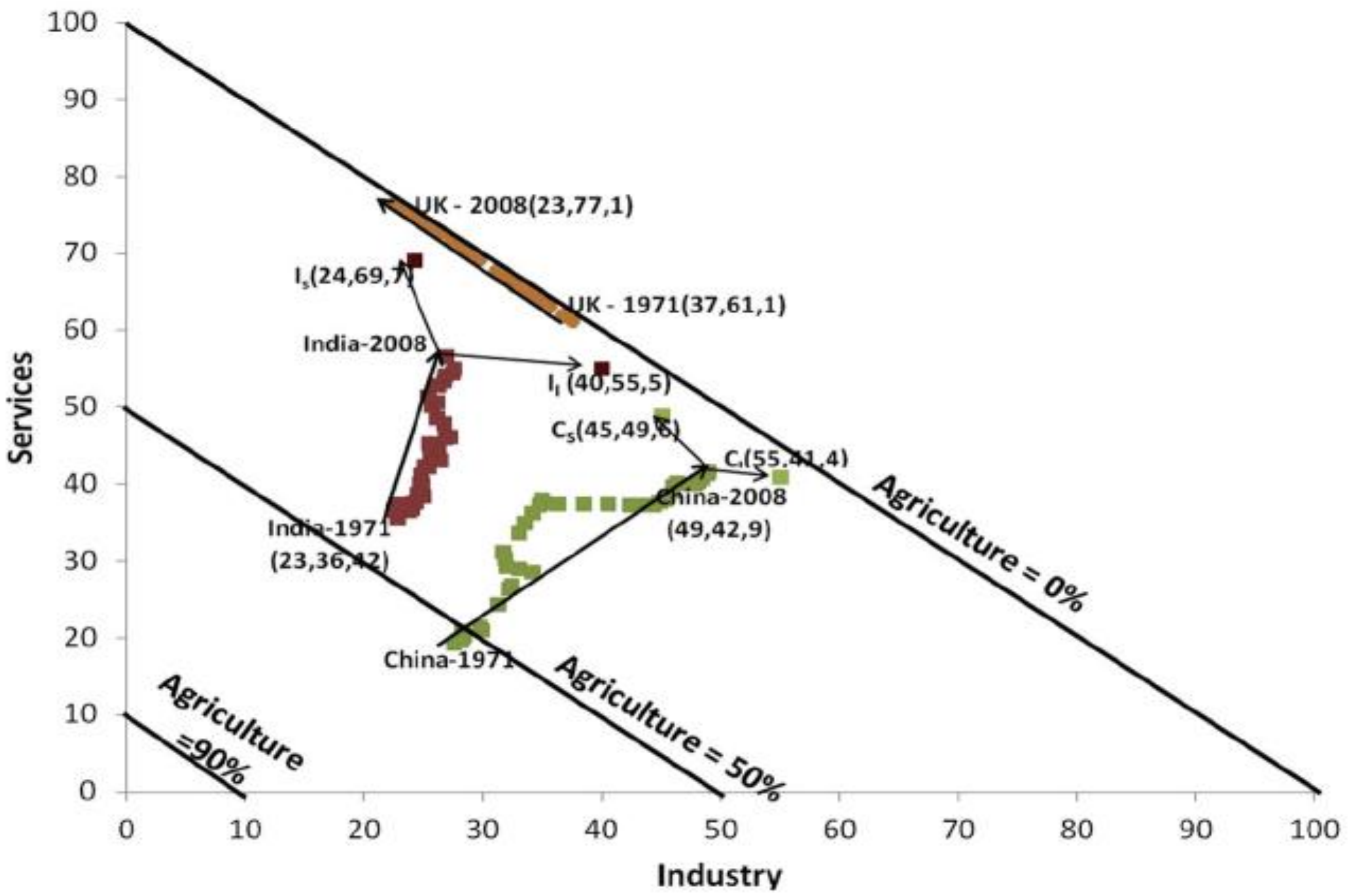
- Decomposition Analysis
- Input-Output Analysis
- Sectoral Optimisation model (Example for Power sector)
- Integrated Modelling Framework

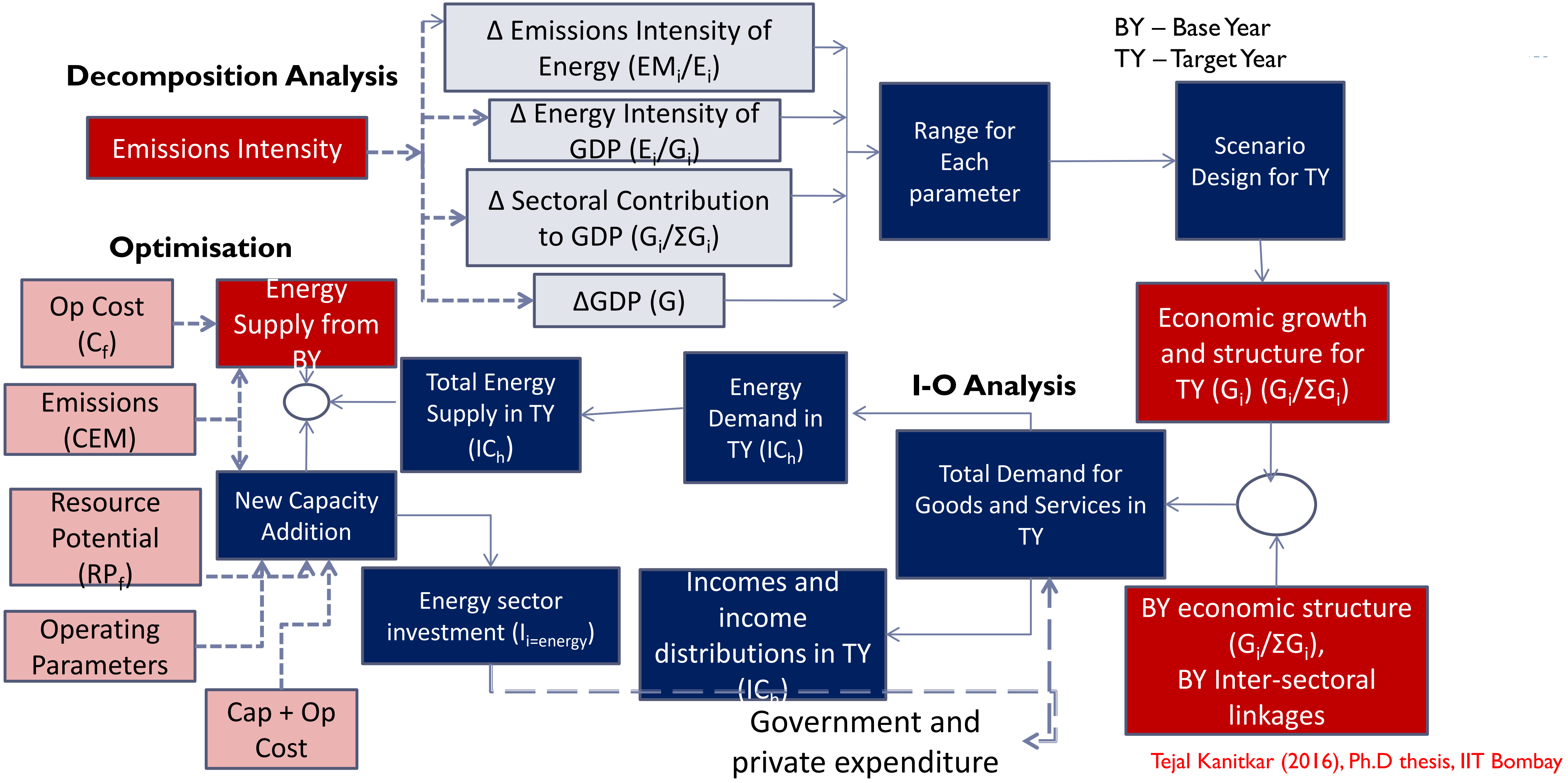
Validation

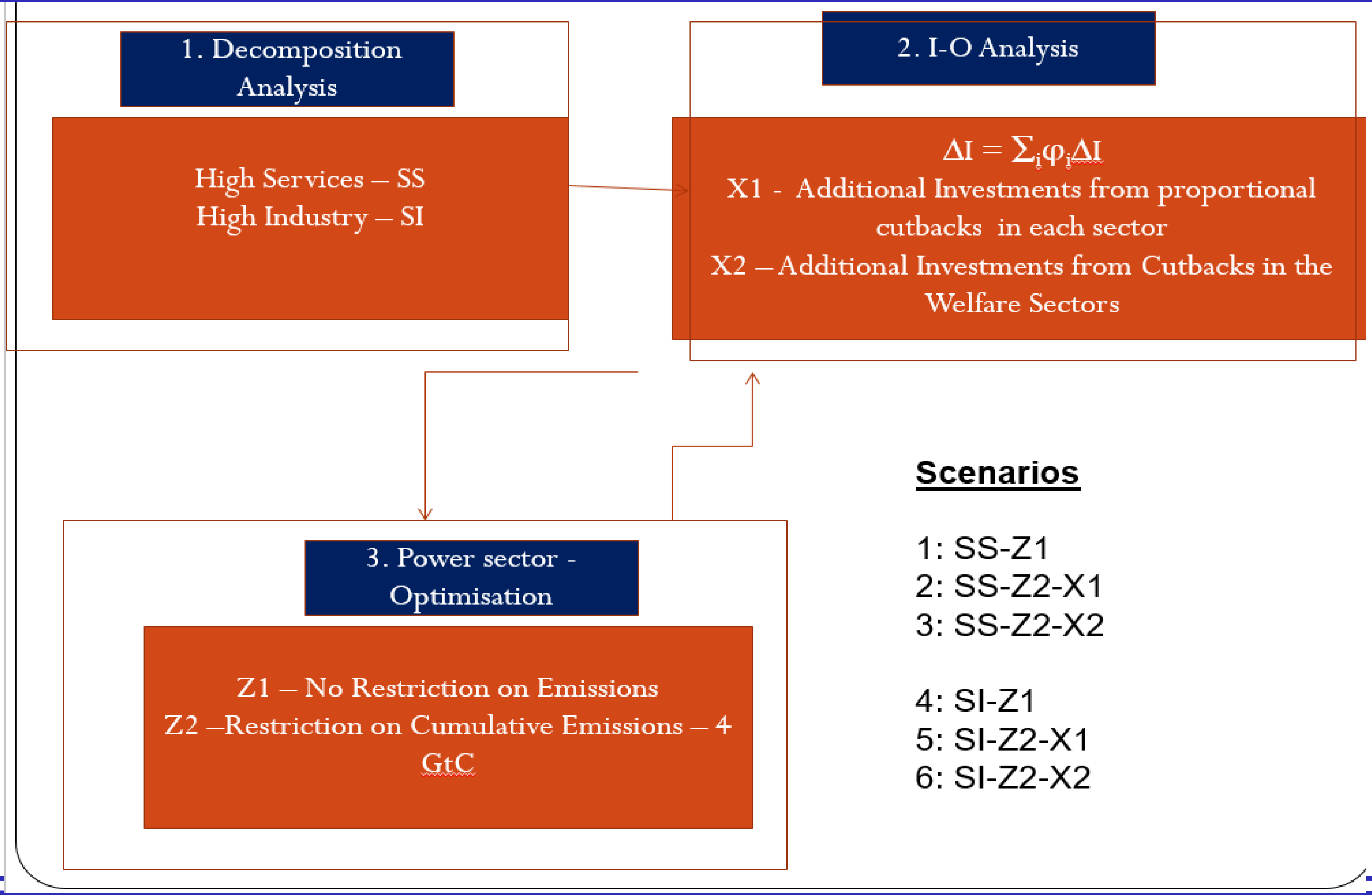
- Individual models compared with literature
- Comparison of sectoral shares globally
- Overall check of reasonableness

Usefulness

- Impact of different development pathways – high industry, high services
- Impact on Inequality – Gini coefficient
- Impact on overall growth rate


100
90
80
70
60
50
40
30
20
10
0
Services
0
10
20
30
40
50
60
70
80
90
100
Industry
UK - 2008(23,77,1)
UK - 1971(37,61,1)
India-2008
India-1971
(23,36,42)
China-2008
(49,42,9)
China-1971
Agriculture = 0%
Agriculture = 50%
Agriculture
=90%


BY – Base Year
TY – Target Year
Decomposition Analysis
Emissions Intensity
Δ Emissions Intensity of Energy (EM_i/E_i)
Δ Energy Intensity of GDP (E_i/G_i)
Δ Sectoral Contribution to GDP ($G_i/\Sigma G_i$)
ΔGDP (G)
Range for Each parameter
Scenario Design for TY
Economic growth and structure for TY (G_i) ($G_i/\Sigma G_i$)
Optimisation
Op Cost (C_f)
Energy Supply from BY
Emissions (CEM)
Resource Potential (RP_f)
Operating Parameters
Cap + Op Cost
New Capacity Addition
Total Energy Supply in TY (IC_h)
Energy Demand in TY (IC_h)
I-O Analysis
Total Demand for Goods and Services in TY
Energy sector investment ($I_{i=energy}$)
Incomes and income distributions in TY (IC_h)
Government and private expenditure
BY economic structure ($G_i/\Sigma G_i$), BY Inter-sectoral linkages
Tejal Kanitkar (2016), Ph.D thesis, IIT Bombay



Scenarios

1: SS-Z1
2: SS-Z2-X1
3: SS-Z2-X2

4: SI-Z1
5: SI-Z2-X1
6: SI-Z2-X2

	Base year	1-SS-Z_1	2-SS-Z_2-X_1
GDP (Billion $)	415	2415	2354
GDP Growth p.a.	-	7.08%	6.98%
Per Capita Income of all Households ($/year/person)	338	1354	1308
Per Capita Income of all Households class RH1($/year/person)	62	185	154
Per Capita Income of all Households RH4 ($/year/person)	354	1662	1600
Per Capita Income of all Households UH1($/year/person)	77	108	92
Per Capita Income of all Households UH3 ($/year/person)	323	1231	1185
GINI Coefficient	0.497	0.531	0.536

- Models – representation of reality
- Improved decision making - component, system design,future sustainable routes, assess impacts, what if?
- Value judgements- trade-offs between criteria-Optimising/ Satisficing
- Blend of models/ prototypes – develop future sustainable energy systems
- Energy Systems in transition – need new modelling approaches

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