Control of Solar Energy Systems

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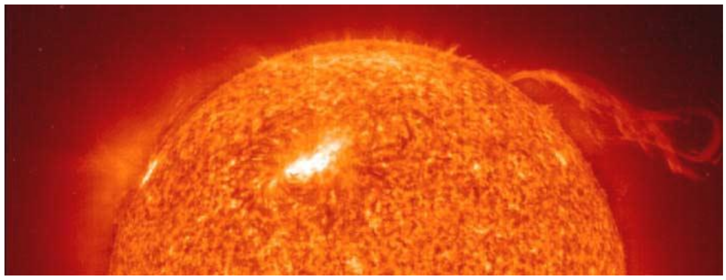
OUTLINE

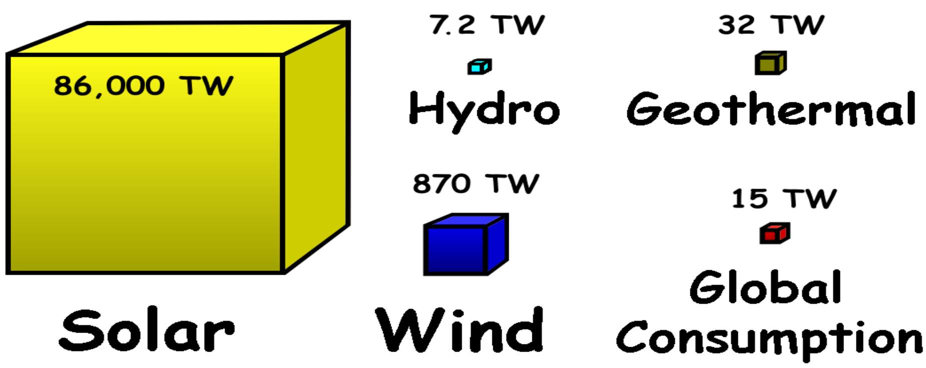
- Solar energy fundamentals
- Thermal Solar plants
- Control problems
- Parabolic trough collector fields
- Conclusions

Here comes the Sun

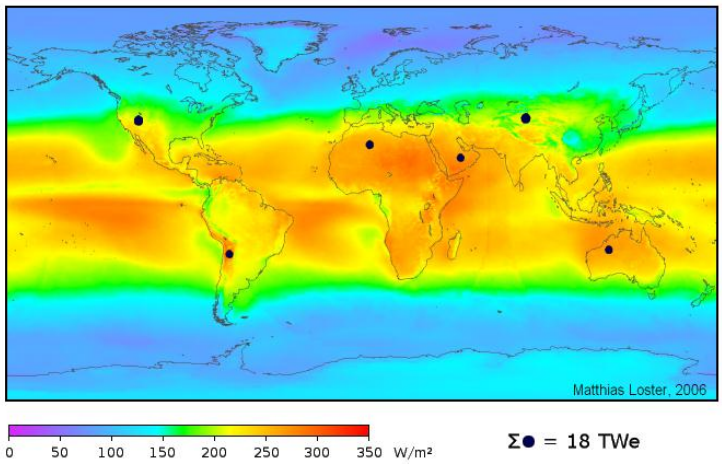


- Accounts for about 98.6% of the Solar System's mass.
- The mean distance from the Earth is approximately 149,600,000 kilometres
- Its light travels this distance in 8 minutes and 19 seconds.
- Consists of hydrogen (74% of its mass, or 92% of its volume), helium (24% of mass, 7% of volume),

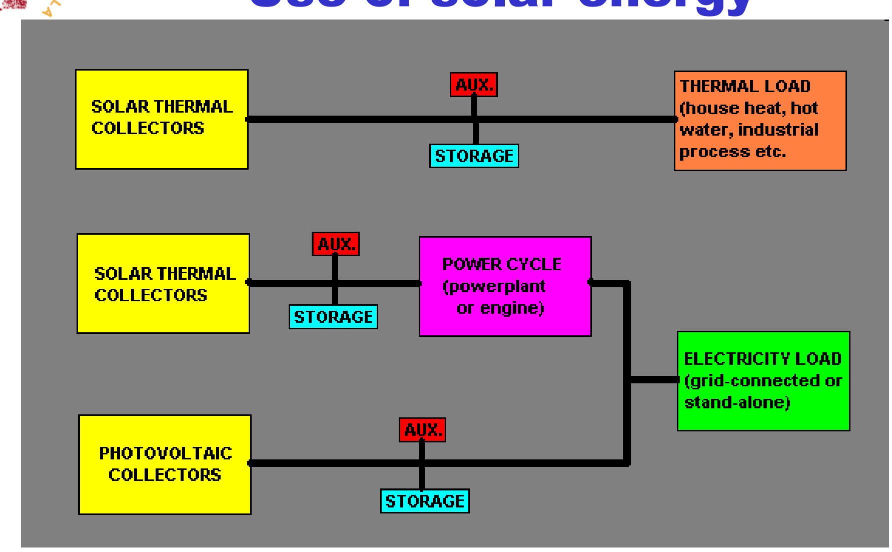
Available Power



Solar power systems covering the dark disks could provide more than the world's total primary energy demand (assuming a conversion efficiency of 8%)

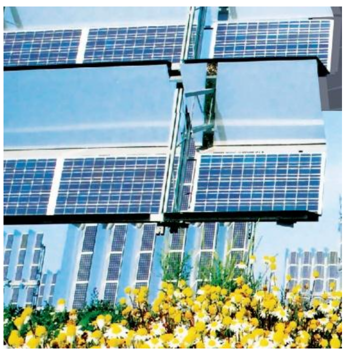


Use of solar energy



Photovoltaic units

Fixed

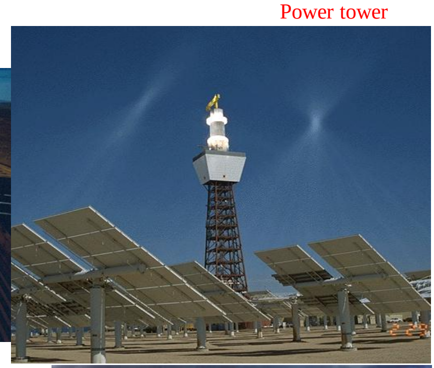


Solar tracking: 1 axis

Solar tracking: 2 axis (and concentration)

Concentrating Solar Power

Power tower

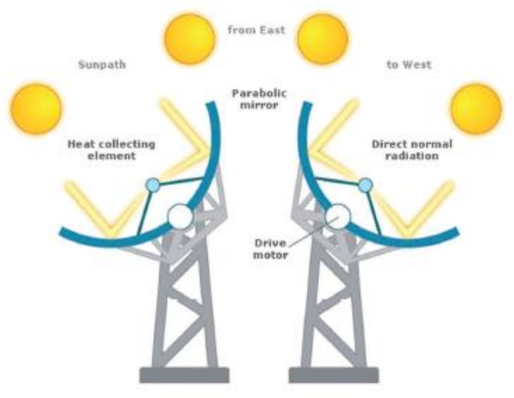


Parabolic trough

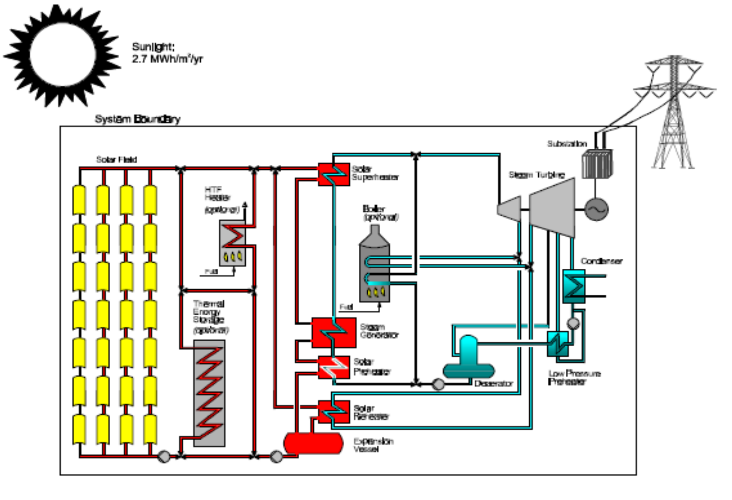
Fresnel

Dish

Parabolic trough collectors



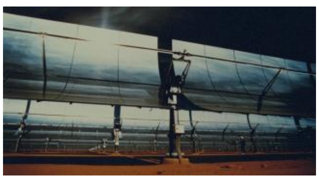
Parabolic trough plants



Parabolic trough plants

- 9 SEGS plants more than 100 plant-years experience.

KJC



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Solar Energy Generating Systems (SEGS)

- 354 MW installed capacity. Nine solar power plants in Mojave desert
- FPL Energy operates and partially owns the plants.
- Average gross solar output 75 MWe — a capacity factor of 21%.
- Turbines can be used at night by burning natural gas.
- 936,384 mirrors cover more than 6.5 km^2.
- Lined up, the parabolic mirrors would extend over 370 km.

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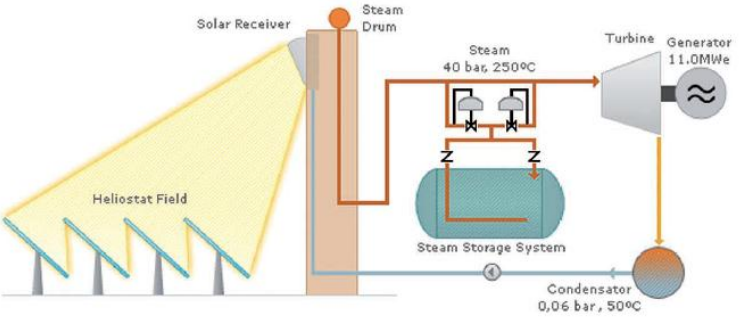
Solar power tower plants



PS 10 (Abengoa)

Increasing size

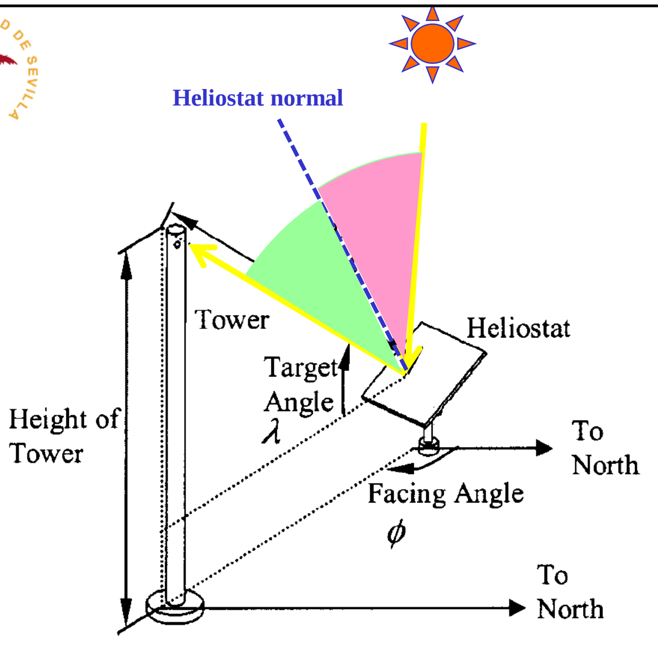
PS20

•1,255 mirrored heliostats

•531 feet-high tower

Control problems in solar systems

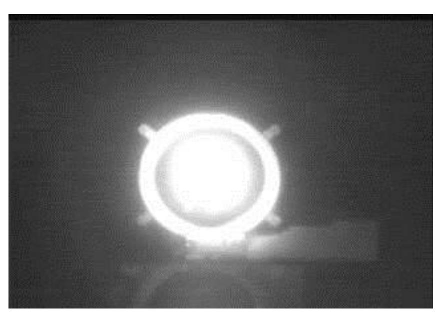
- **Collectors movement (sun tracking)**
  - **Slow**
  - **Open loop (almost)**
- **Temperature and pressure control**
  - **Rich dynamics (PDEs, deadtimes, nonlinear, ...)**
  - **High disturbances**
  - **Closed loop (almost)**



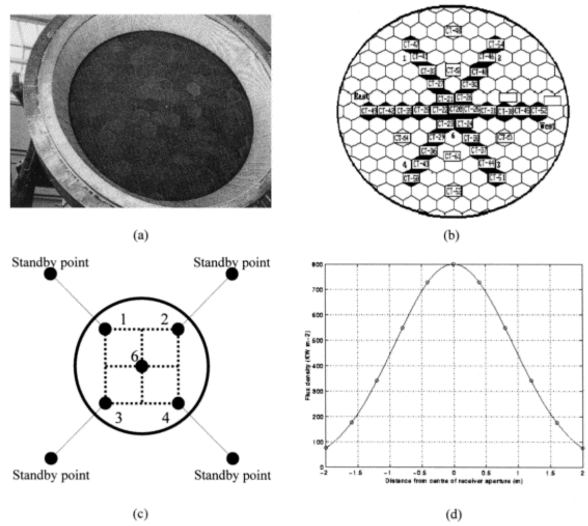
Solar platform of Almeria (PSA) (desert of Tabernas)

Some feedback in heliostat solar tracking

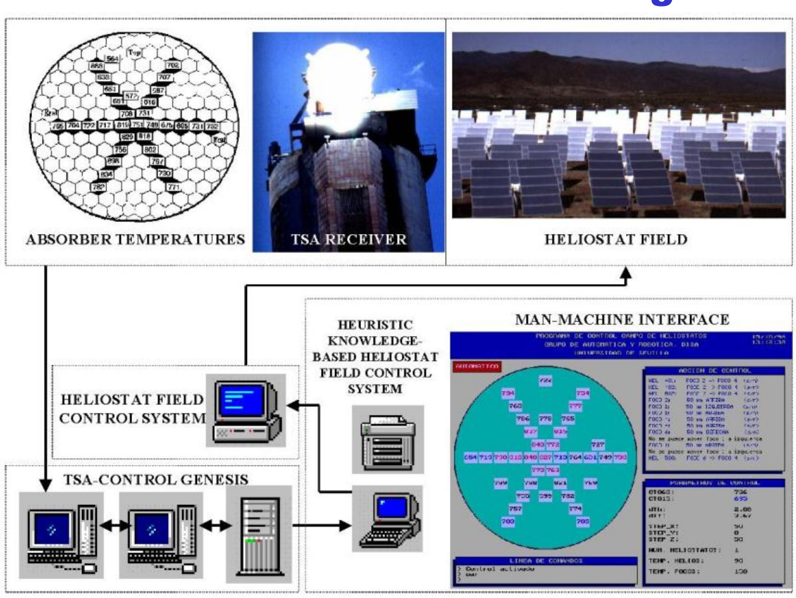
Receiver feedback: uniform heating



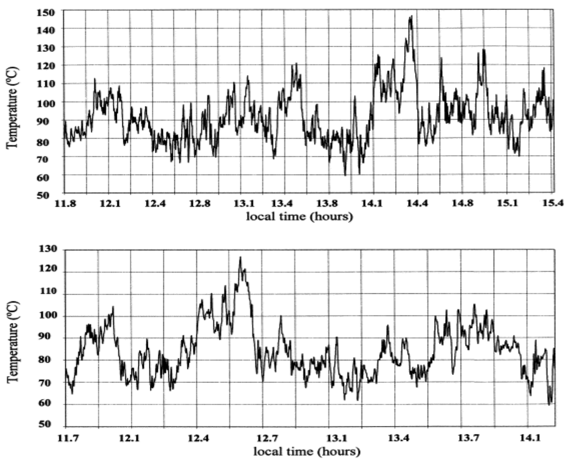
Uniform receiver heating

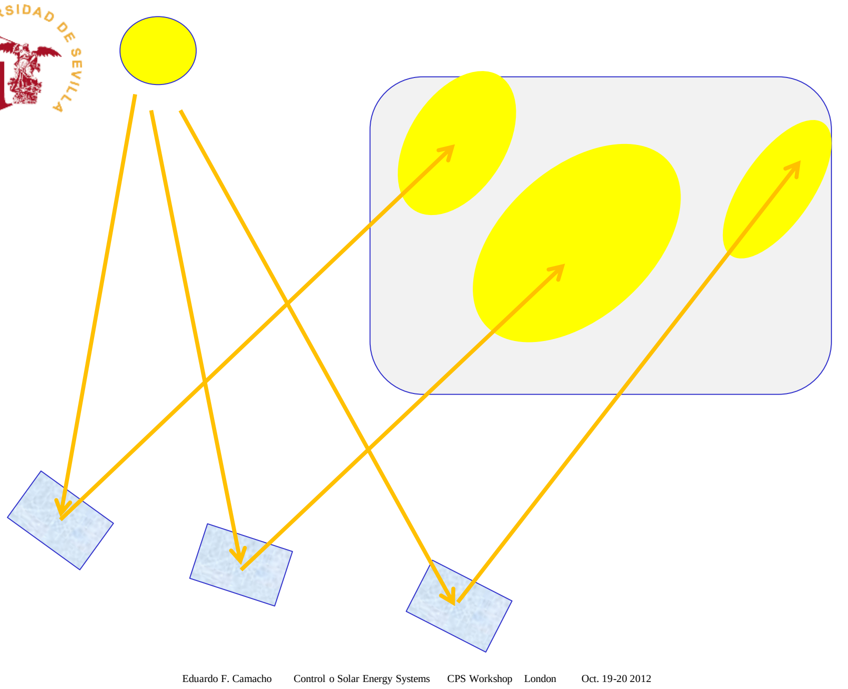


Uniform receiver heating

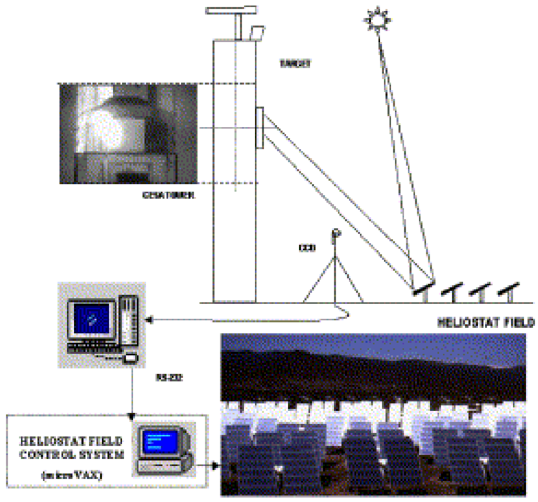


Max temperature deviation (automatic mode)

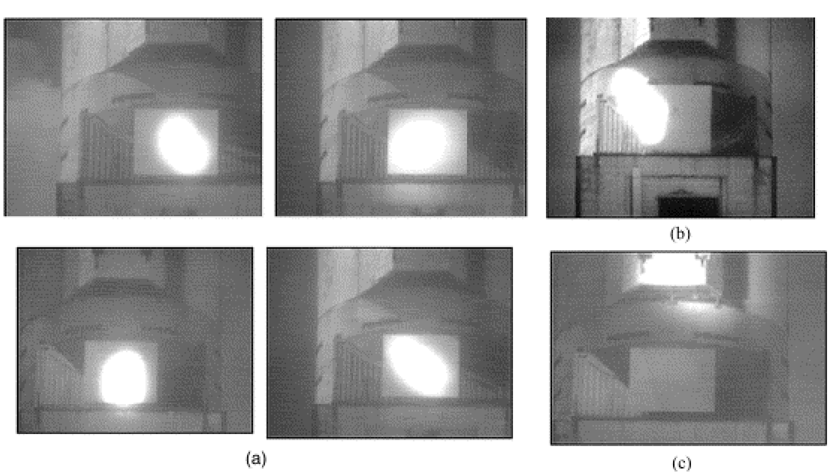




Heliostat calibration

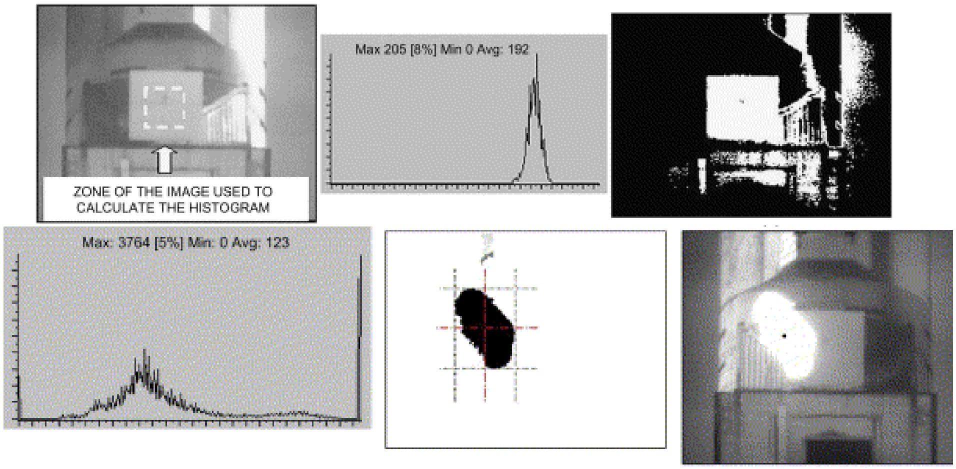


Heliostat calibration



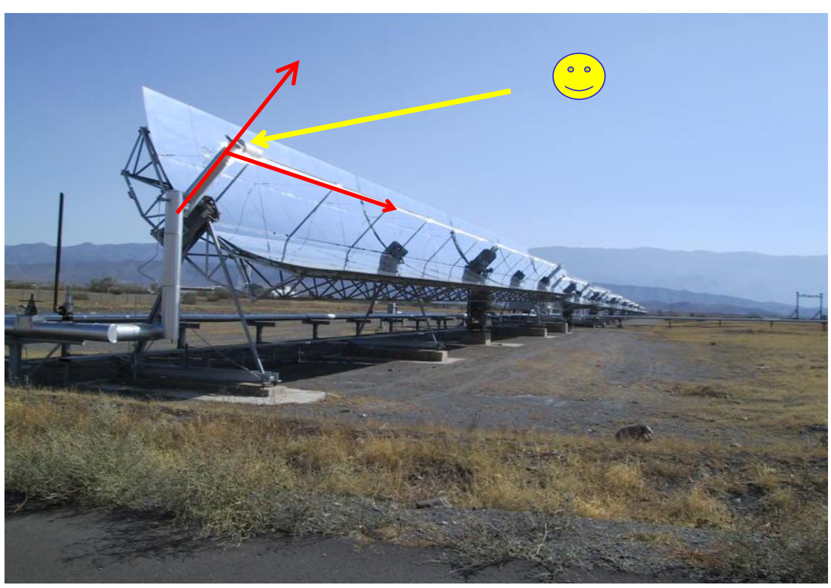
(a) (b) (c)

Blob centroid computation

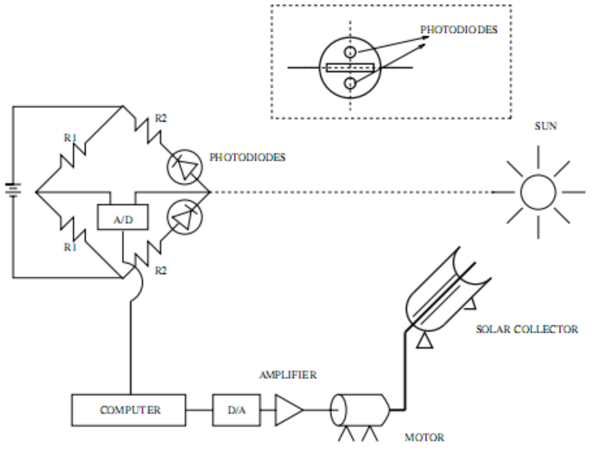


(a) (b) (c)

Parabolic trough collectors



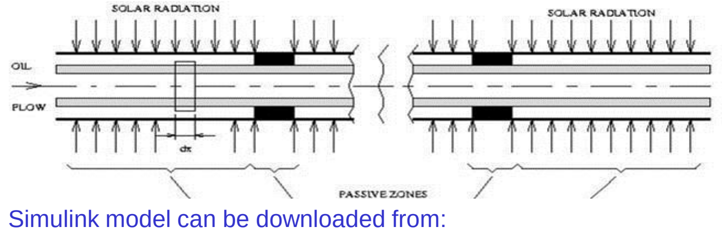
Parabolic trough fine tracking



Process model

Metal: $\rho_m C_m A_m \partial T_m / \partial t = \eta_o I G - G H_l(T_m - T_a) - L H_t(T_m - T_f)$

Fluid: $\rho_f C_f A_f \partial T_f / \partial t + \rho_f C_f q \partial T_m / \partial x = L H_t(T_m - T_f)$

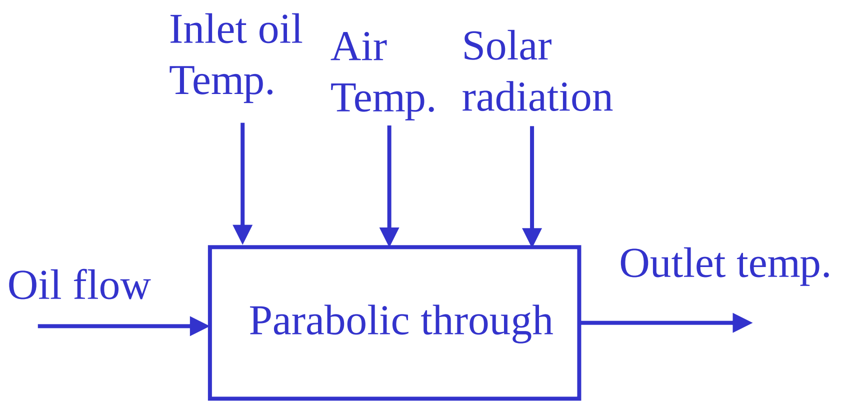


Simulink model can be downloaded from:

E.F. Camacho, *et al.* Advanced Control of Solar Power Plants, Springer, 1997

http://www.esi2.us.es/~eduardo/libro-s/libro.html

Solar field



Why controlling the solar plants is a challenge ?

- **The energy source is not a manipulated variable but a perturbation !**
- **Complex dynamics: Non linear, PDE, dead time, never at a steady state**
- **Constraints (operating closed to constraints)**
- **Deciding the operating mode is part of the control strategy.**

Many contributors and …
many control techniques !

- R. Carmona (1985)
- F.R. Rubio (1985)
- J.A. Gutierrez (1987)
- M. Hughes (1992)
- M. Berenguel (1995)
- J. Normey (1997)
- M. R. Arahal (1997)
- L. Valenzuela (2005)
- E. Zarza (2005)
- C. M. Cirre (2006)
- M.P. Parte (2005)
- I. Alvarado (2008)
- ….

- J. M. Lemos (1997)
- E. Mosca (1998)
- R.N. Silva (1997)
- L.M. Rato (1997)
- A.L. Cardoso (1999)
- A. Dourado (1999)
- T.A. Jonahansen (2000)
- M. Brao (2000)
- E. Juuso (2000)
- I. Farkas (2002)
- I. Vajk (2002)
- L. Yebra (2005)
- ….

Model Predictive Control

- <u>MPC successful in industry</u>.
  - Many and very diverse and successful applications:
    - Refining, petrochemical, polymers, ,
    - Semiconductor production scheduling,
    - Air traffic control
    - ….
  - Many MPC vendors
- <u>MPC successful in Academia</u>
  - Many MPC sessions in control conferences and control journals,
  - 4/8 finalist papers for the *CEP best paper award* were MPC papers (2/3 finally awarded were MPC papers)

MPC

- Process model $x(t+1)=f(x(t),u(t),e(t))$
  $y(t)=g(x(t),u(t),e(t))$
- Cost function

$$J(u,t)=\sum_{j=N_1}^{N_2}\left[y_{t+j}-r_{t+j}\right]^2+\sum_{j=1}^{N_u}\lambda\left[\Delta u_{t+j-1}\right]^2$$

- Prediction equation (linear) $\mathbf{y}=G\,\mathbf{u}+F\,x(t)+E\,\mathbf{e}$
  (Free and forced response)
- $\mathbf{u}^*=\arg\min_{\mathbf{u}} J(\mathbf{u},x(t))$

MPC and solar power plants

Level 1: planner
- Power computarion
- Horizon 24 hours

Level 2: optimizer
- Set point optimization
- Horizon 2 hours

level 3: Regulation
- Keep variables closed to set points
- Horizon 30 minutes

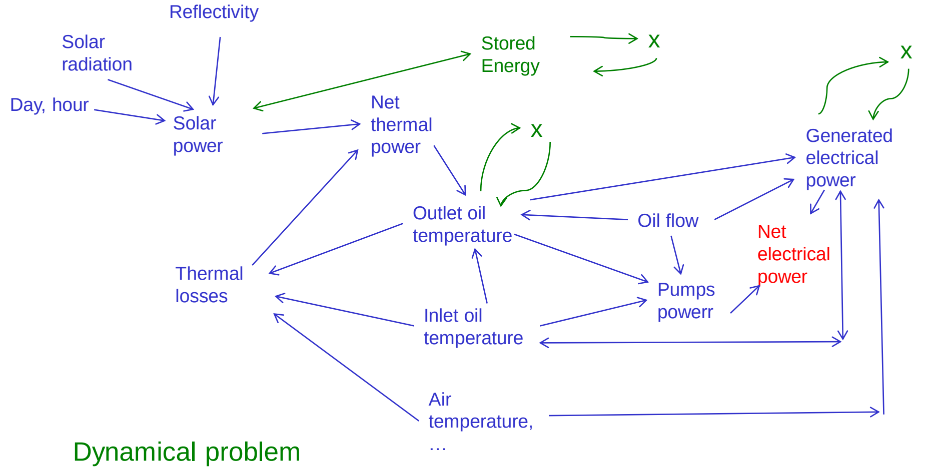
Level 1: Planning

$$I_i = \sum_{t=1}^{n} E_s(t)e_1(t) + E_{stored}(n)e_s - \sum_{t=1}^{n} |E_s(t) - E_{contracted}(t)|\, e_2(t)$$

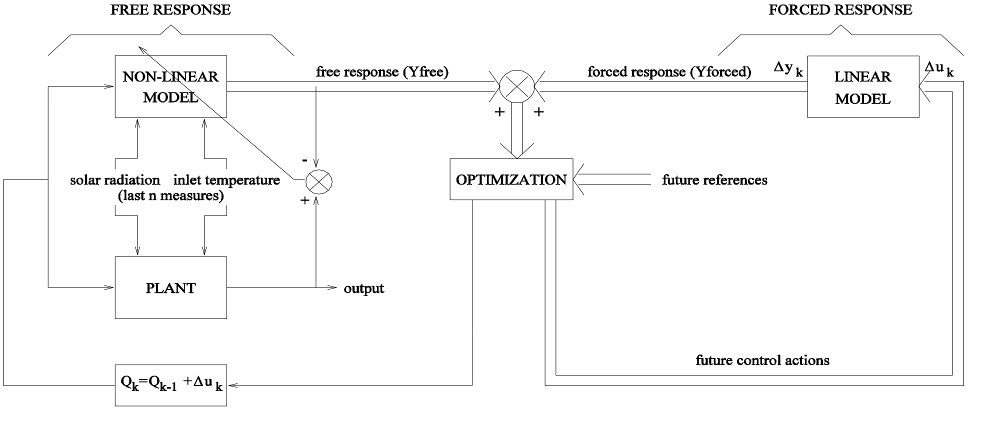
$$\max \sum_{t=1}^{n} E_s(t)e_1(t) + \left[E_{stored}(0)(1-\alpha)^n + \sum_{i=1}^{n} E_{stored}(i)(1-\alpha)^{n-i}\right] e_s$$

$$- \sum_{t=1}^{n} |E_s - E_{contracted}| e_2(t)$$

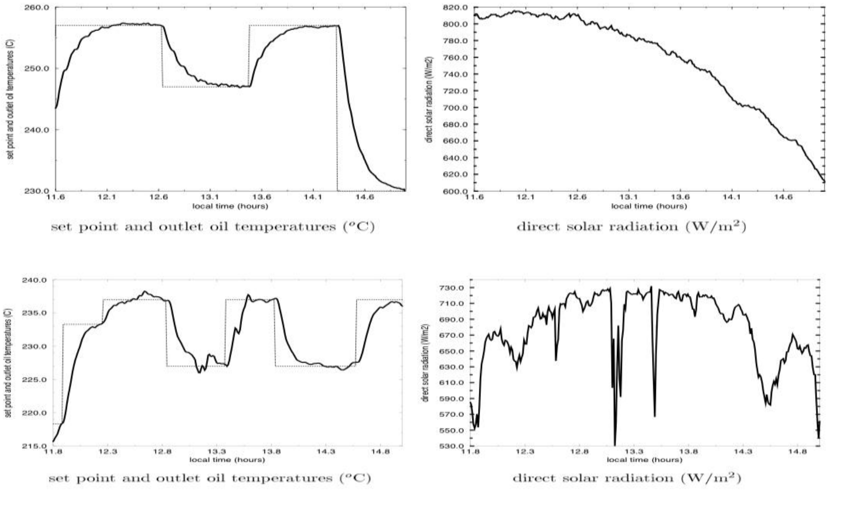
Level 2: Optimal operating points



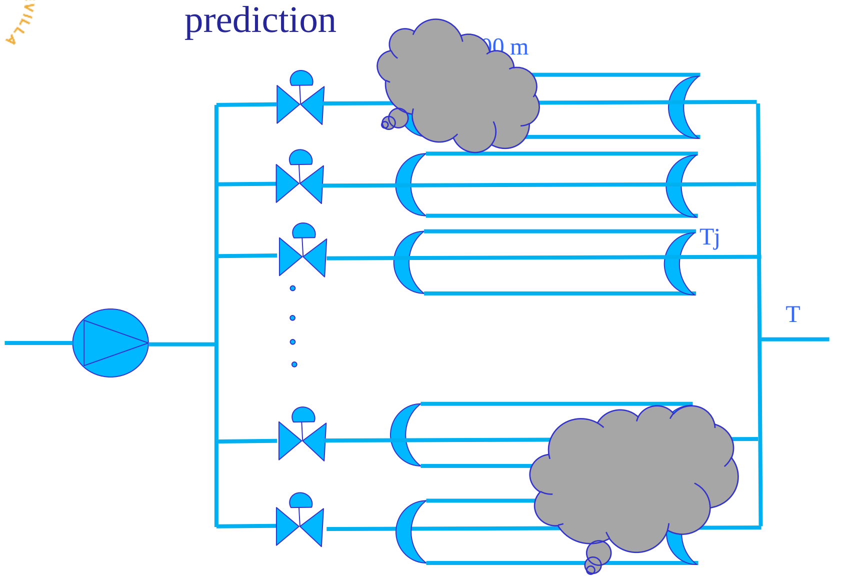
NMPC computation



Level 3: Regulación
(MPC)

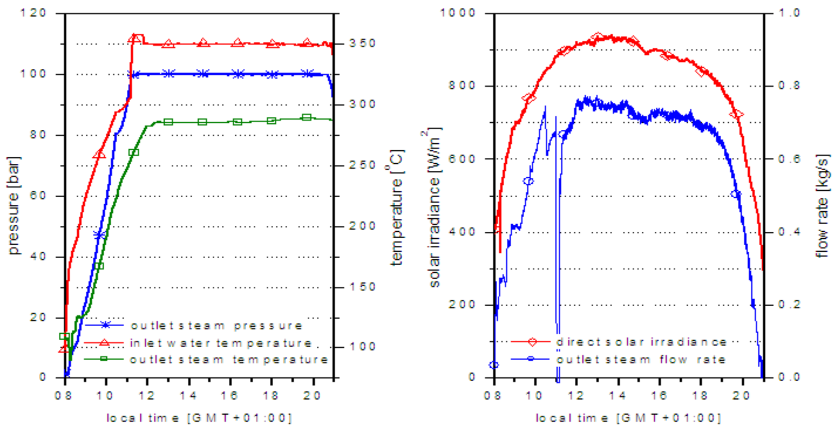


Distributed sensing and control and prediction



Level 3: Regulation DISS 350 ºC y 100 bars

Level 3: Regulation DISS
350 ºC y 100 bars



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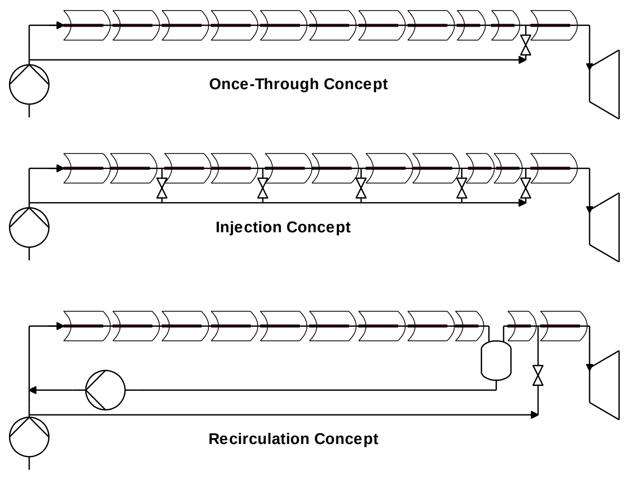
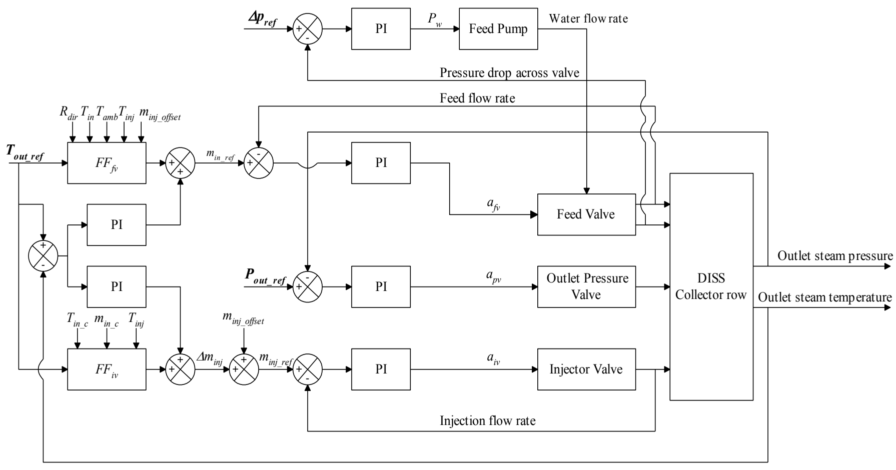
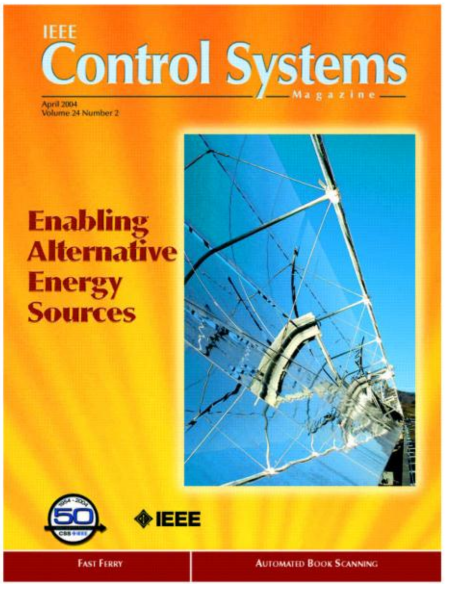
DISS operating modes



One through control





Conclusions

Solar energy is looking bright but ....

... needs to reduce costs and increase availability. Control systems helps to enable solar technolgy

Many results but still many open problems.

Thanks !

Some references:

E.F. Camacho, M Berenguel and F.R. Rubio. Advanced Control of Solar Power Plants, Springer, 1977

E.F. Camacho, M Berenguel and F.R. Rubio and L. Valenzuela, *A survey on control schemes for distributed solar collector fields.* (*Part I and Part II)*. Solar Energy, vol 81, 2007

E.F. Camacho, M Berenguel, F.R. Rubio and D. Martinez, Control of Solar Energy Systems, Springer, 2012.

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