On the (intelligent) control of solar thermal plants.

Eduardo F. Camacho

University of Seville

Spain

OUTLINE

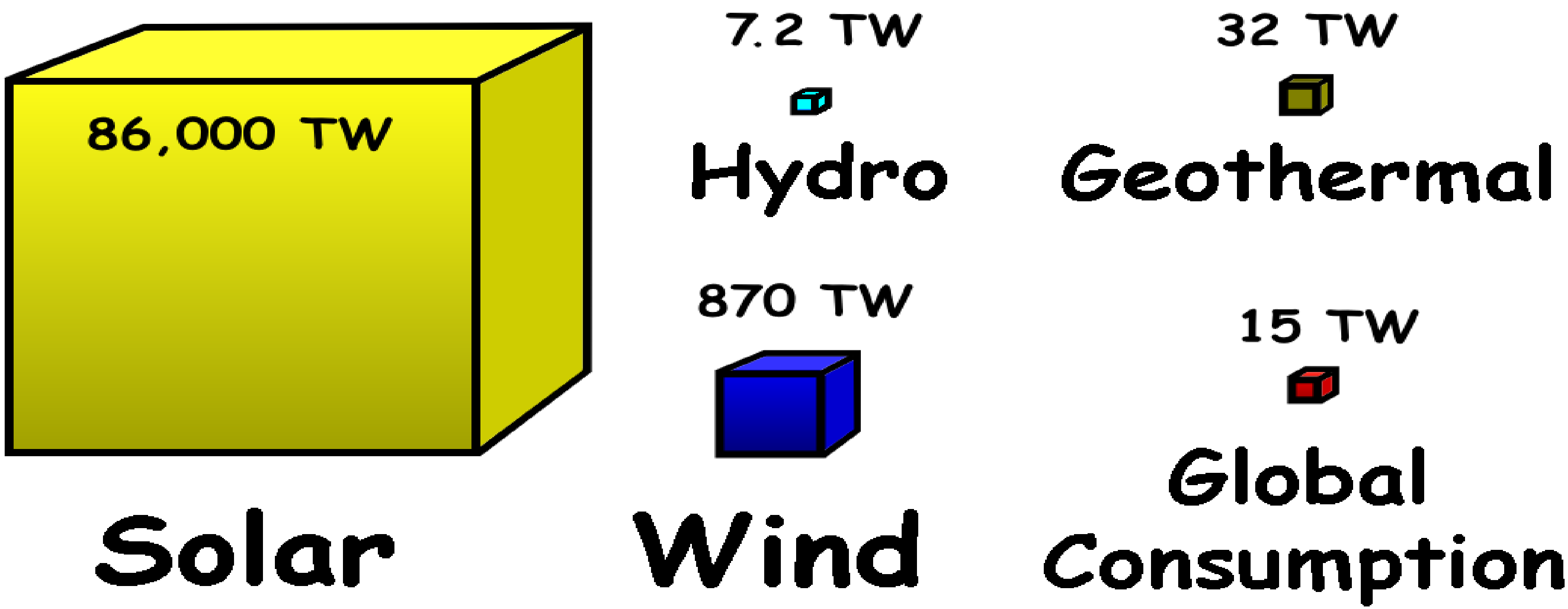
- Solar energy
- Thermal Solar plants control issues
- Parabolic trough plants
- Control experiences on commercial plants
- ERC Advanced Grant OCONTSOLAR
- Conclusions

Woody Allen:

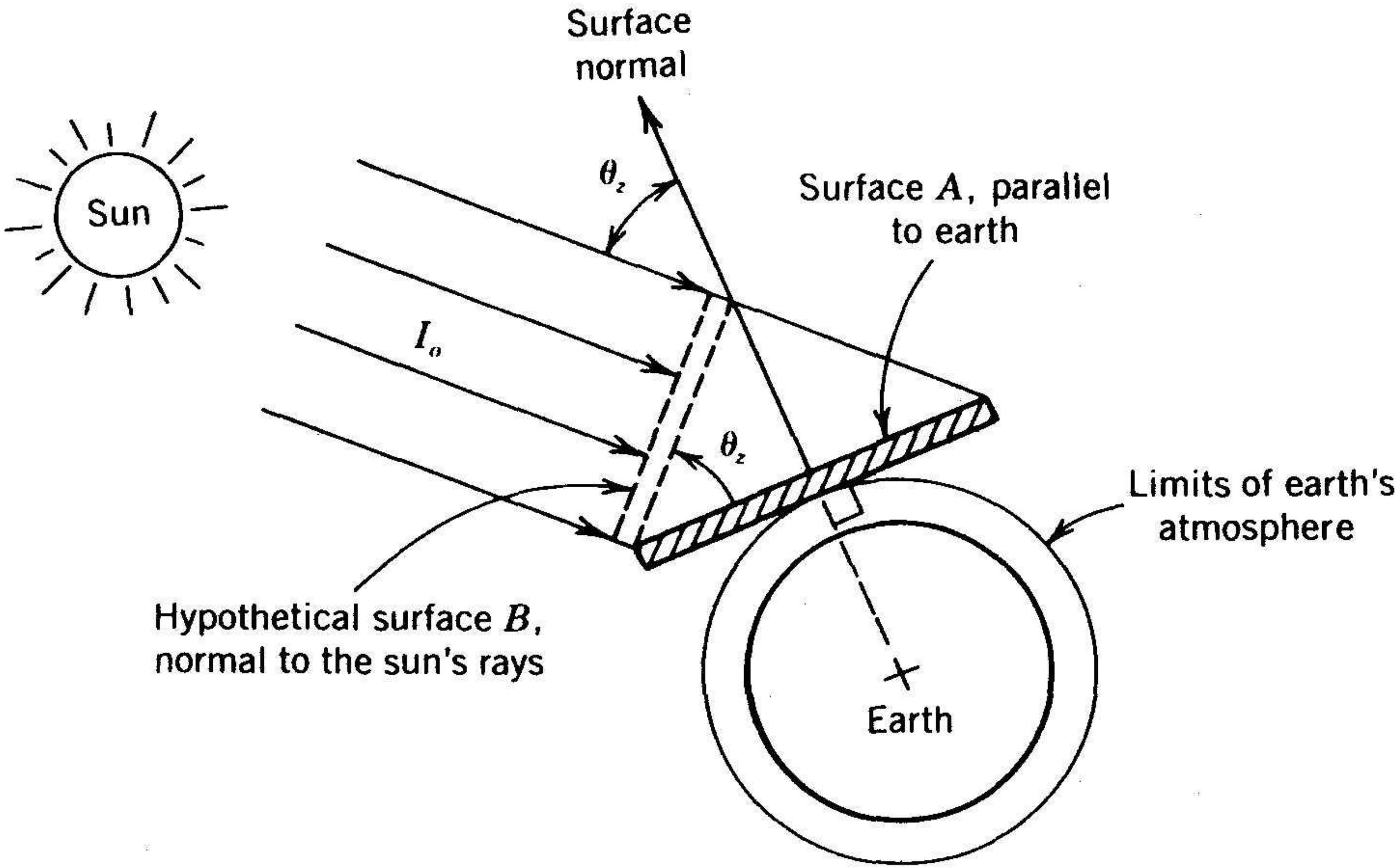
"I took a speed reading course and read 'War and Peace' in twenty minutes. ...

….. It involves Russia."

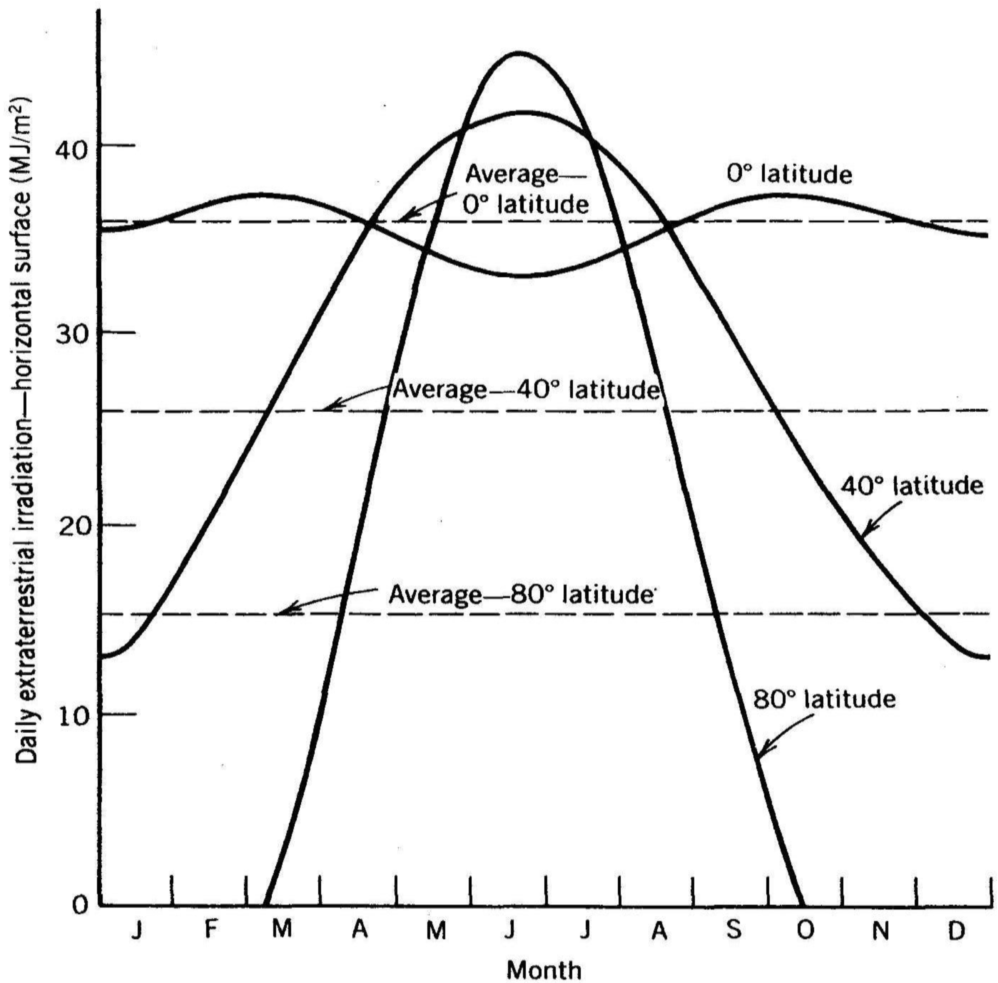
Available Power



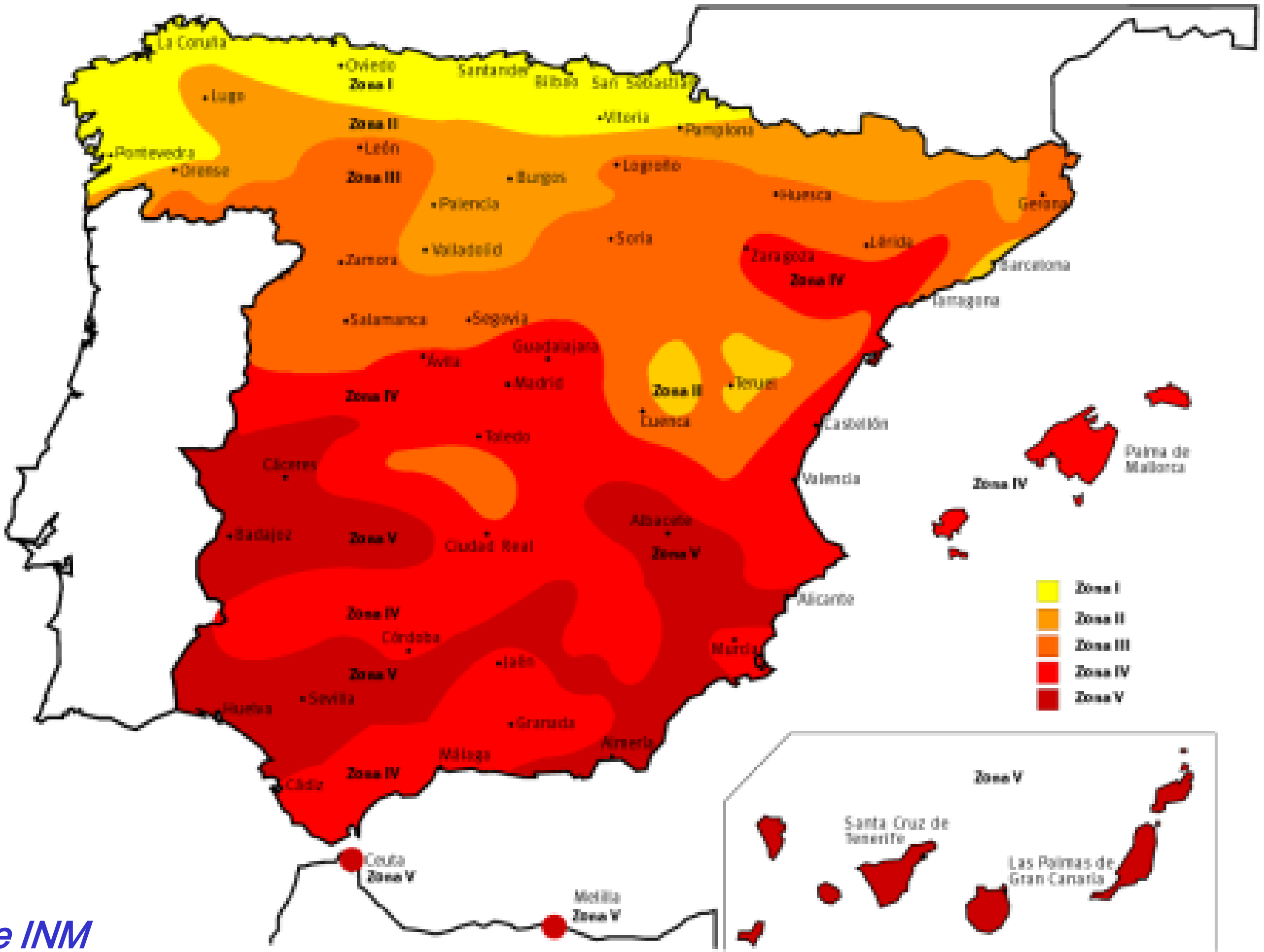
The cosine factor



Extraterrestial daily solar radiation and latitude



Average daily solar energy in Spain



Zona I: H < 3,8

Zona II: 3,8 ≤ H <4,2

Zona III: 4,2 ≤ H < 4,6

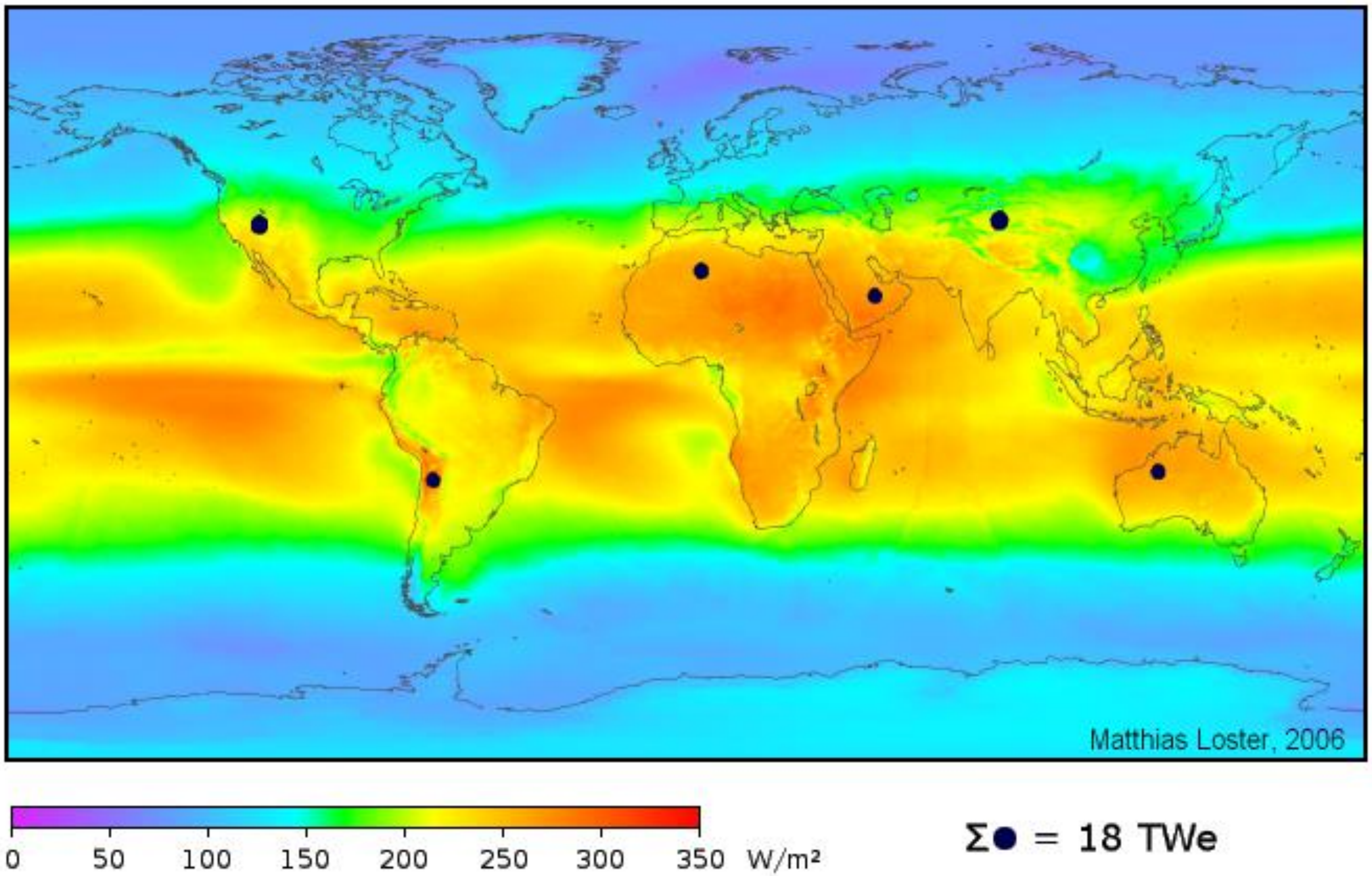
Zona IV: 4,6 ≤ H<5,0

Zona V: H ≥ 5,0

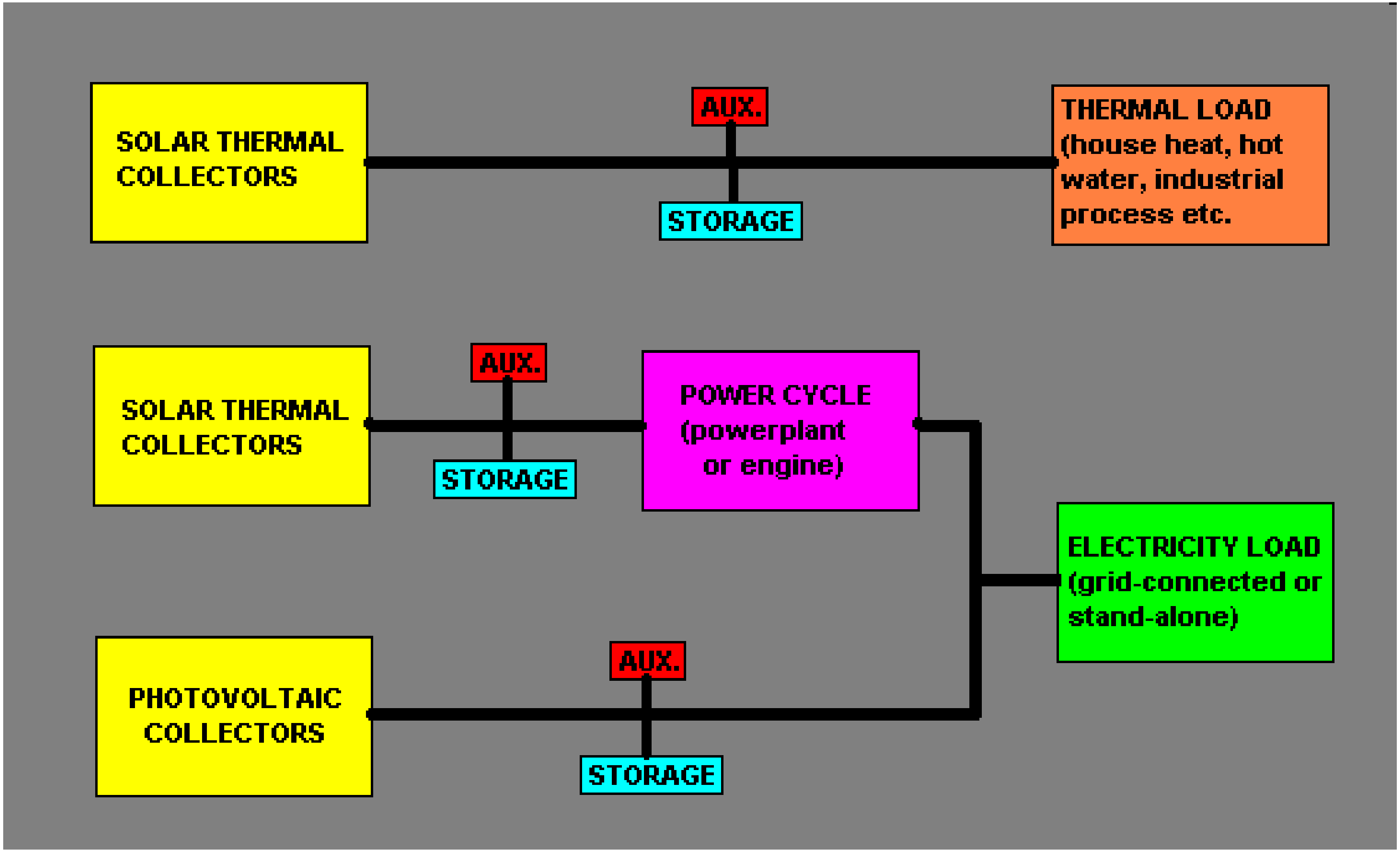
H se mide en kWh/m²

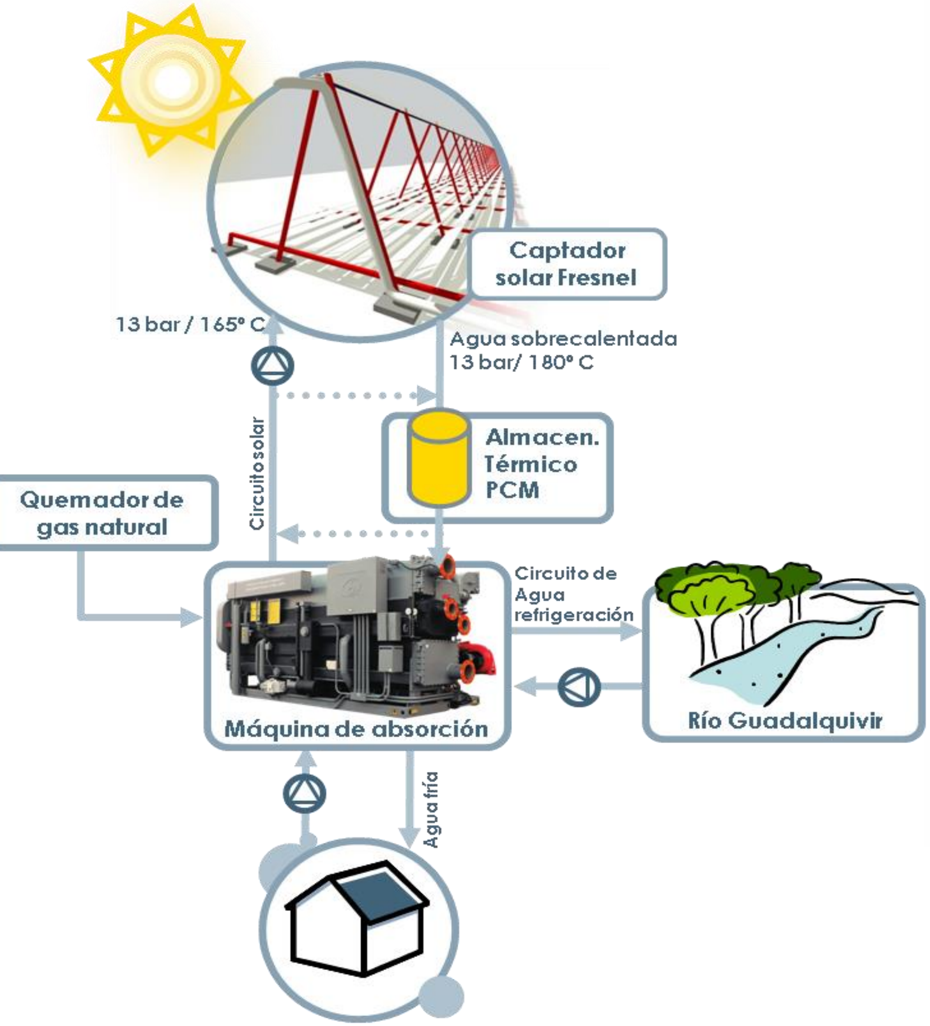
Source INM

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




Captador solar Fresnel
13 bar / 165º C
Agua sobrecalentada 13 bar/ 180º C
Almacen. Térmico PCM
Circuito solar
Quemador de gas natural
Circuito de Agua refrigeración
Máquina de absorción
Río Guadalquivir
Agua fría

Photovoltaic units

Fixed

Solar tracking: 1 axis

Solar tracking: 2 axis (and concentration)

Concentrating Solar Power

Power tower

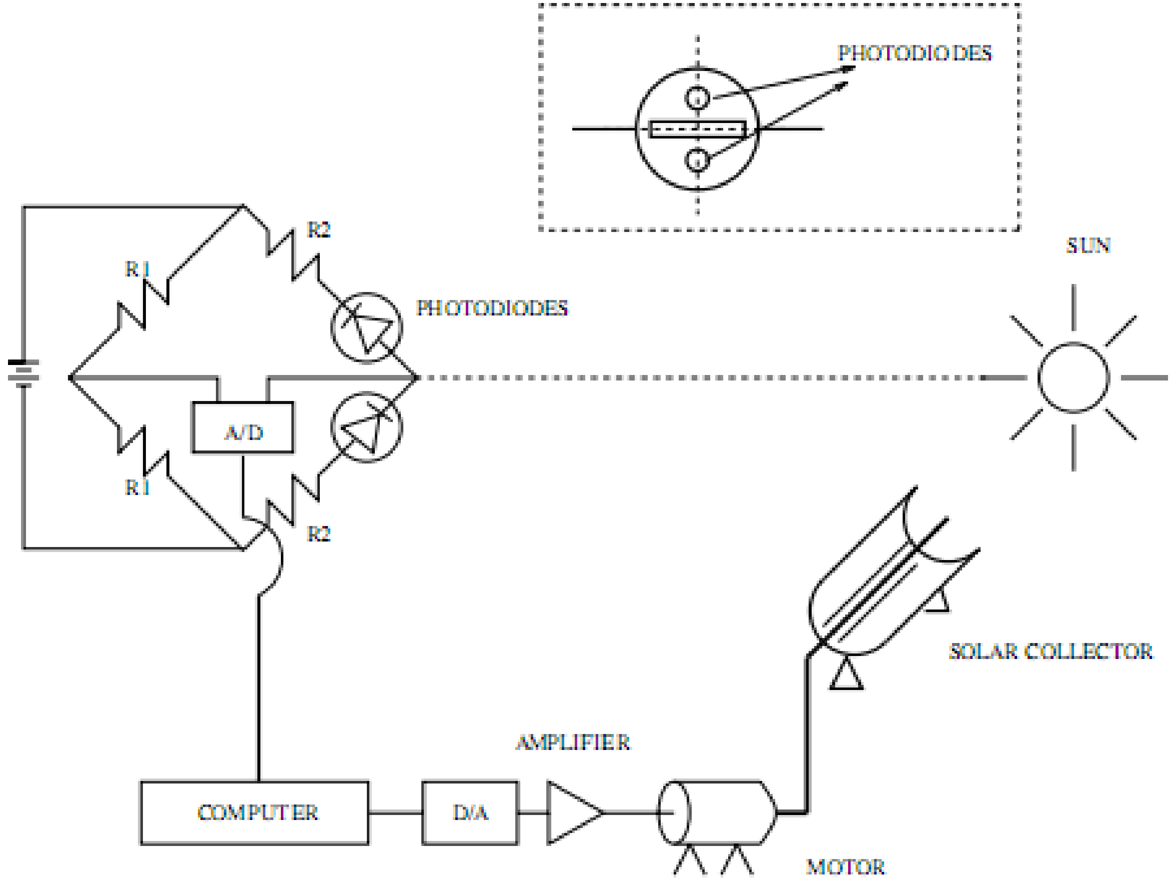
Parabolic trough

Control problems in solar systems

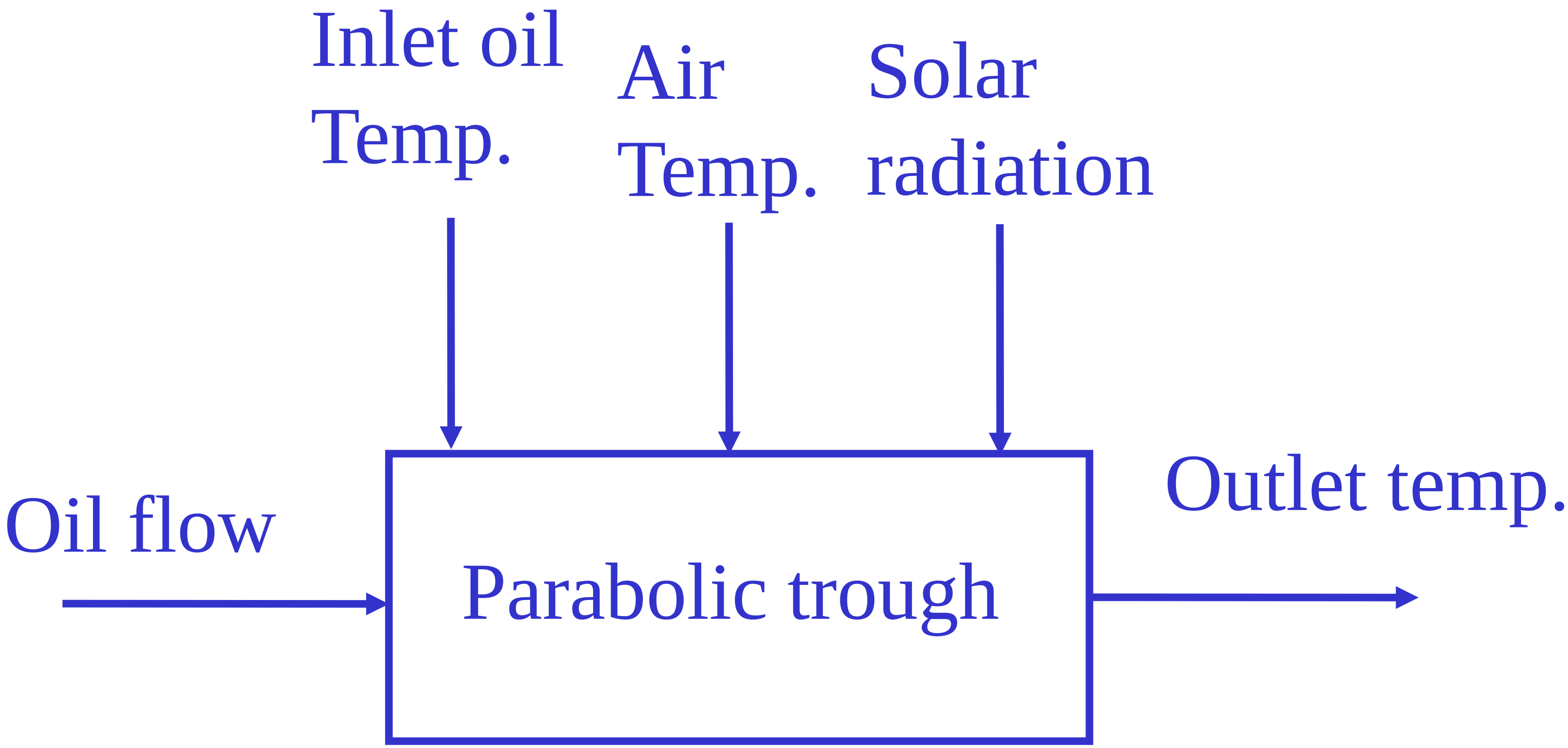
- Collectors movement (sun tracking)
  - Slow
  - Open loop (most of the time)

- Control of thermodynamic variables
  - Rich dynamics (PDEs, deadtimes, nonlinear, ...)
  - High disturbances
  - Closed loop (most of the time)

Parabolic trough fine tracking



Solar field

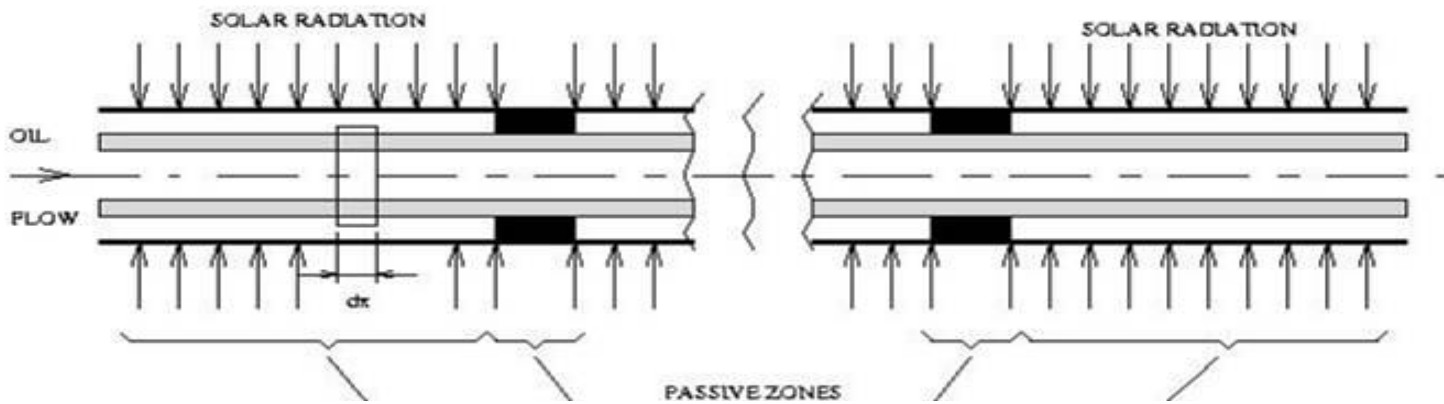


Inlet oil Temp.
Air Temp.
Solar radiation
Oil flow
Parabolic trough
Outlet temp.

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

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 (when to store energy).

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)
- A. Gallego (2012-)
- L. Yebra (2017)
- J.R.D Frejo (2020)
- E. Masero (2021)
- S. R. Moreno(2021)
- A.S. del Pozo (2017- ..)
- J. M. Escaño (2019- ..)
- …

- 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)
- ….

…

MPC successful in industry.

Many and very diverse and successful applications:

- Petrochemical, polymers,
- Semiconductor production,
- Air traffic control
- Clinical anesthesia,
- ….
- Life Extending of Boiler-Turbine Systems via Model Predictive Methods, Li et al (2004)

Many MPC vendors

IFAC Pilot Industry Committee

Chaired by Tariq Samad (Honeywell), 28 total: 15 industry, 12 academia, 1 gov't;

Members asked to assess impact of several advanced control technologies:

Q1 Responses [23 responses]

- **PID control: 23 High-impact**
- **Model-predictive control: 18 High-impact; 2 No/Lo impact**
- **System identification: 14 High-impact; 2 No/Lo impact**
- **Process data analytics: 14 High-impact; 4 No/Lo impact**
- **Soft sensing: 12 High-impact; 5 No/Lo impact**
- **Fault detection and identification [22]: 11 High-impact; 4 No/Lo impact**
- **Decentralized and/or coordinated control: 11 High-impact; 7 No/Lo impact**
- **Intelligent control: 8 High-impact; 7 No/Lo impact**
- **Discrete-event systems [22]: 5 High-impact; 7 No/Lo impact**
- **Nonlinear control: 5 High-impact; 8 No/Lo impact**
- **Adaptive control: 4 High-impact; 10 No/Lo impact**
- **Hybrid dynamical systems: 3 High-impact; 10 No/Lo impact**
- **Robust control: 3 High-impact; 10 No/Lo impact**

Why is MPC so successful ?

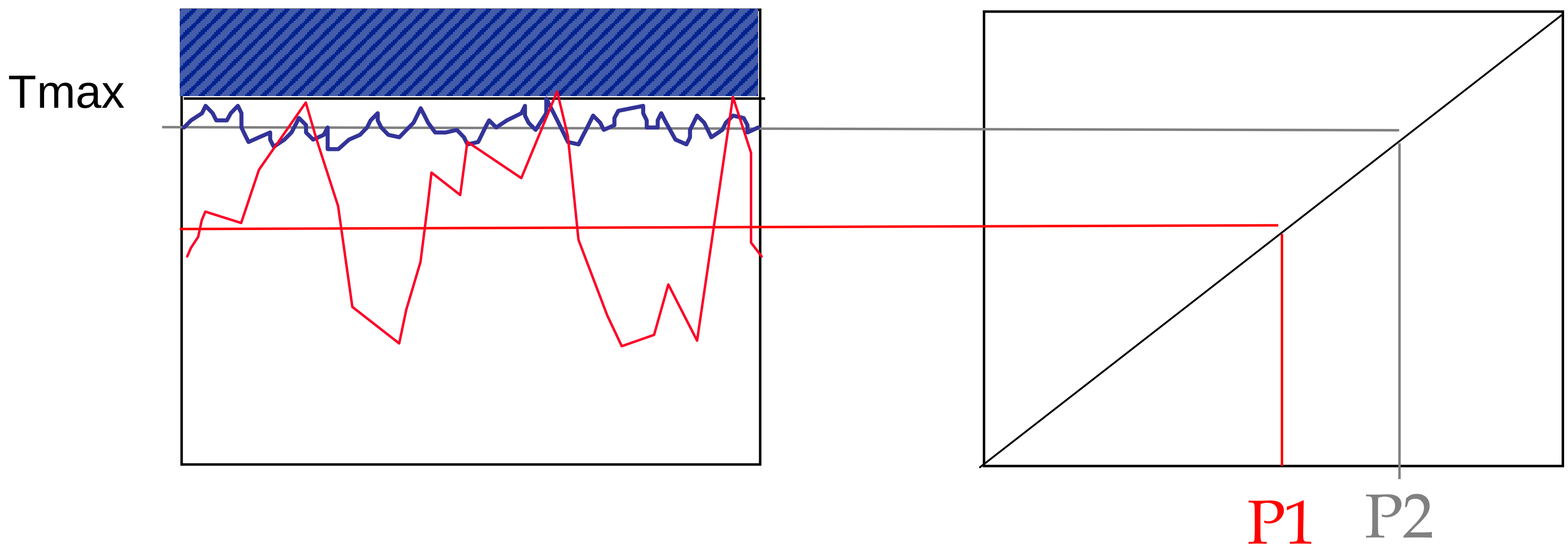
- MPC is Most general way of posing the control problem in the time domain:
  - Optimal control
  - Stochastic control
  - Known references
  - Measurable disturbances
  - Multivariable
  - Dead time
  - Constraints
  - Uncertainties

Real reason of success: Economics

MPC can be used to optimize operating points (economic objectives). Optimum usually at the intersection of a set of constraints.

Obtaining smaller variance and taking constraints into account allow to operate closer to constraints (and optimum).

Repsol reported 2-6 months payback periods for new MPC applications.

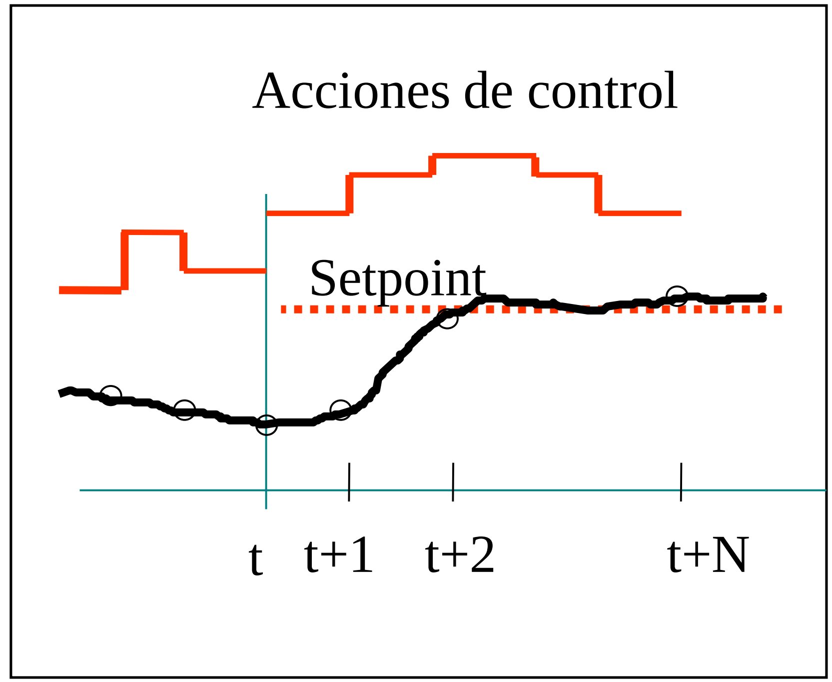


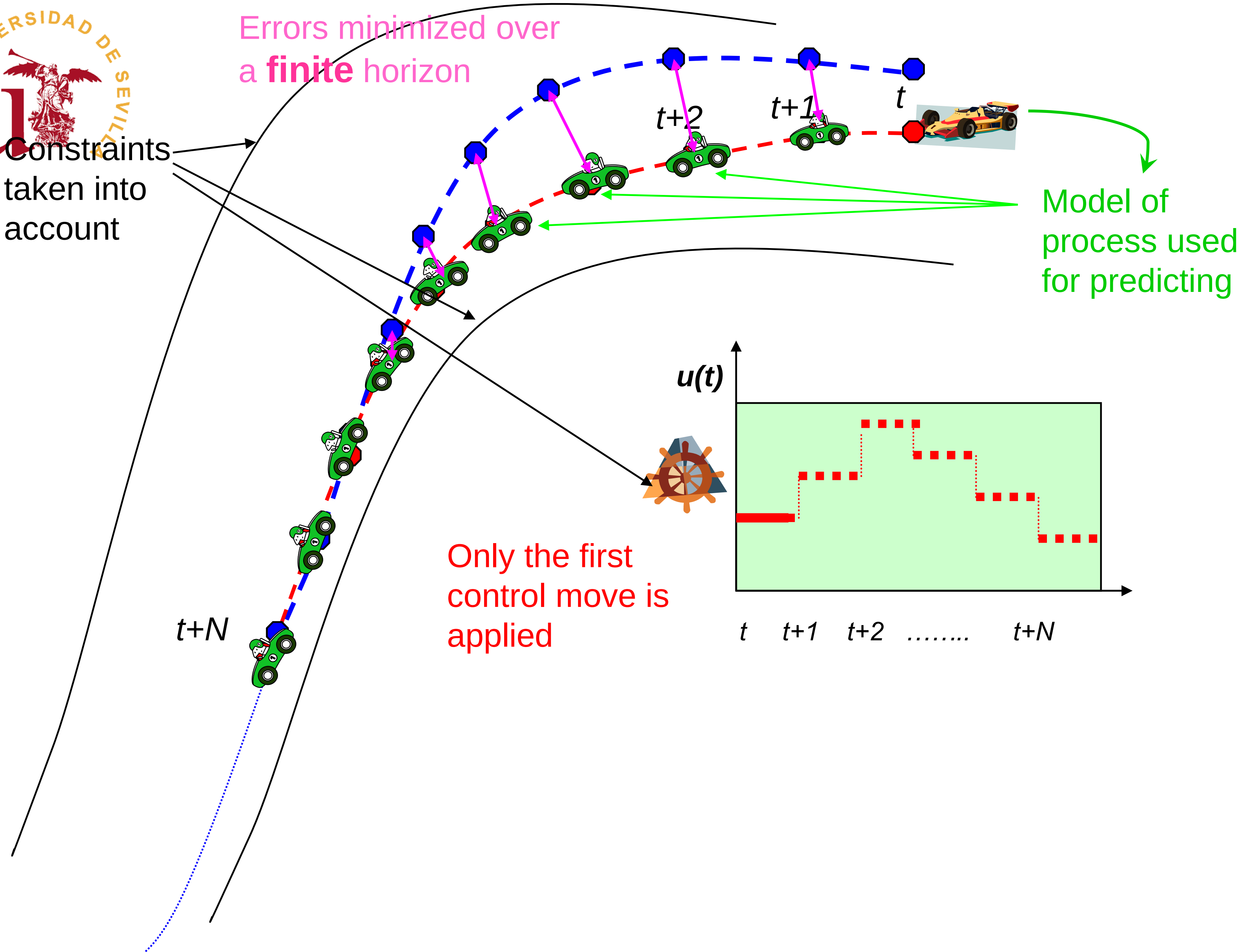
MPC strategy

At sampling time *t the future control sequence is compute so that the future sequence of predicted output y(t+k/t) along a horizon N follows the future references as best as possible.*

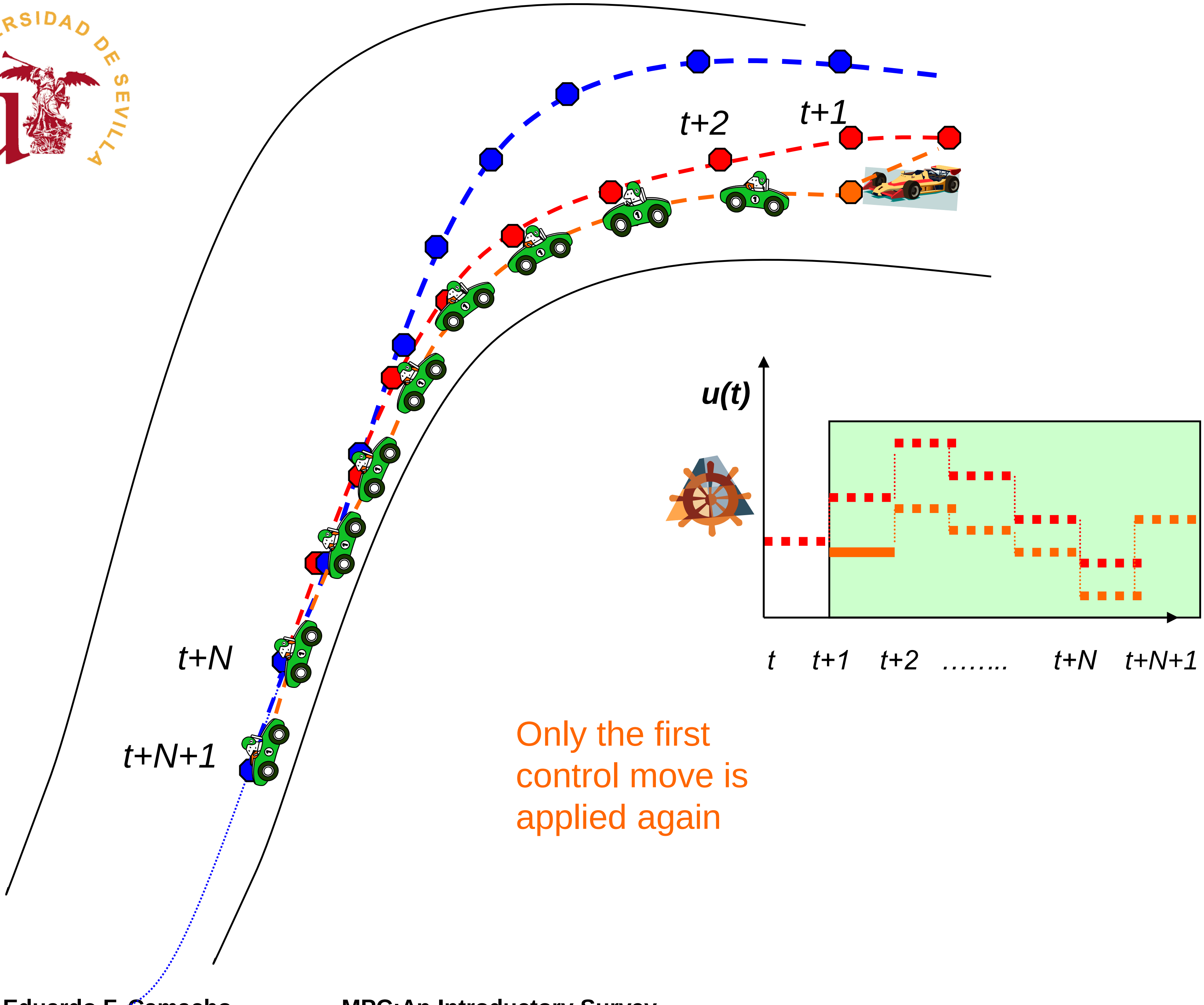
The first control signal is used and the rest disregarded.

The process is repeated at the next sampling instant *t+1*





Errors minimized over a **finite** horizon
Constraints taken into account
t+2
t+1
t
Model of process used for predicting
u(t)
Only the first control move is applied
t+N
t t+1 t+2 …….. t+N



Only the first control move is applied again

MPC strategy

1. Optimization problem $P_N(x,\Omega)$:

$$u^* = \arg\min_u \sum_{(i=0,\ldots,N-1)} l(x(i),u(i)) + F(x(N))$$

Operating constaints .

$$x(i) \in X,\ u(i) \in U,\ \ i=0,\ldots,N-1$$

Terminal constraint (stability): $x(N) \in \Omega$

2. Apply the receding horizon control law: $K_N(x)=u^*(0)$.

Linear MPC

f(x,u) is an affine function (model)

X,U,Ω are polytope (constraints)

l and ***F*** are quadratic functions ***(***or ***1-norm*** or ***∞-norm*** functions***)***

$$\Downarrow$$

QP or LP

Otherwise

If ***f(x,u)*** is not an affine function

Or any of ***X,U,Ω*** are not polyhedra

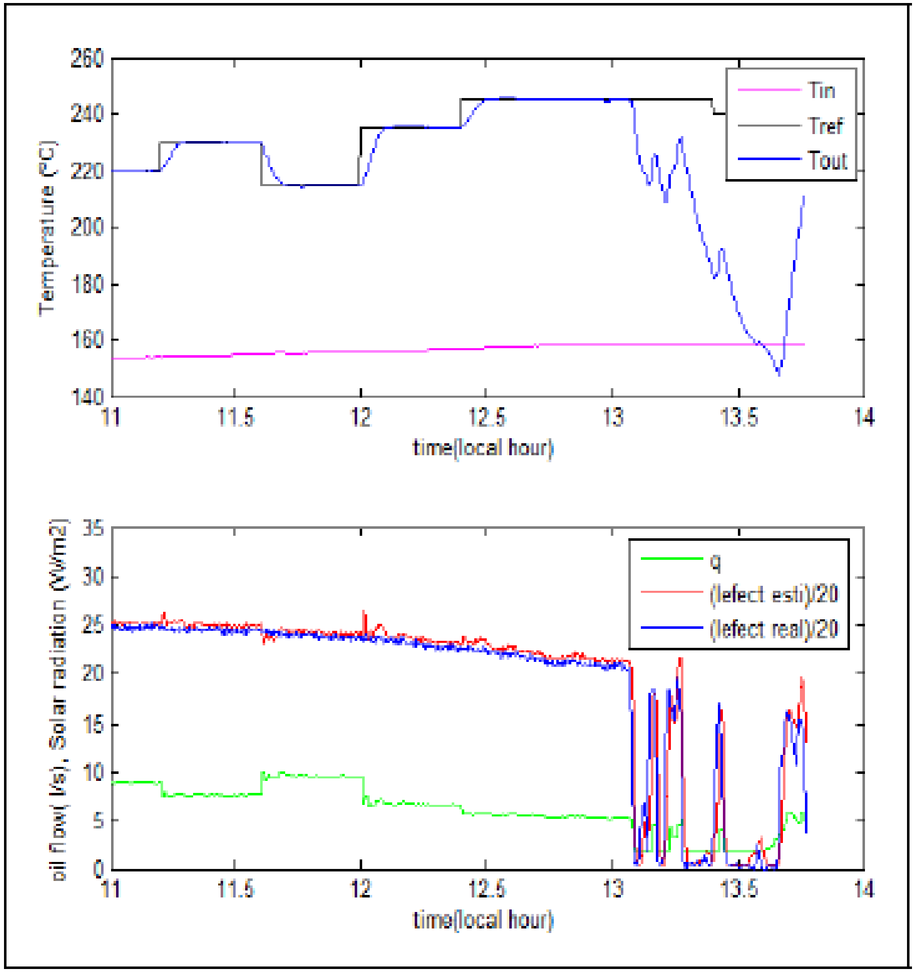
Or any of ***l*** and ***F*** are not quadratic functions ***(***or ***1-norm*** or ***∞-norm*** functions***)***

$$\Downarrow$$

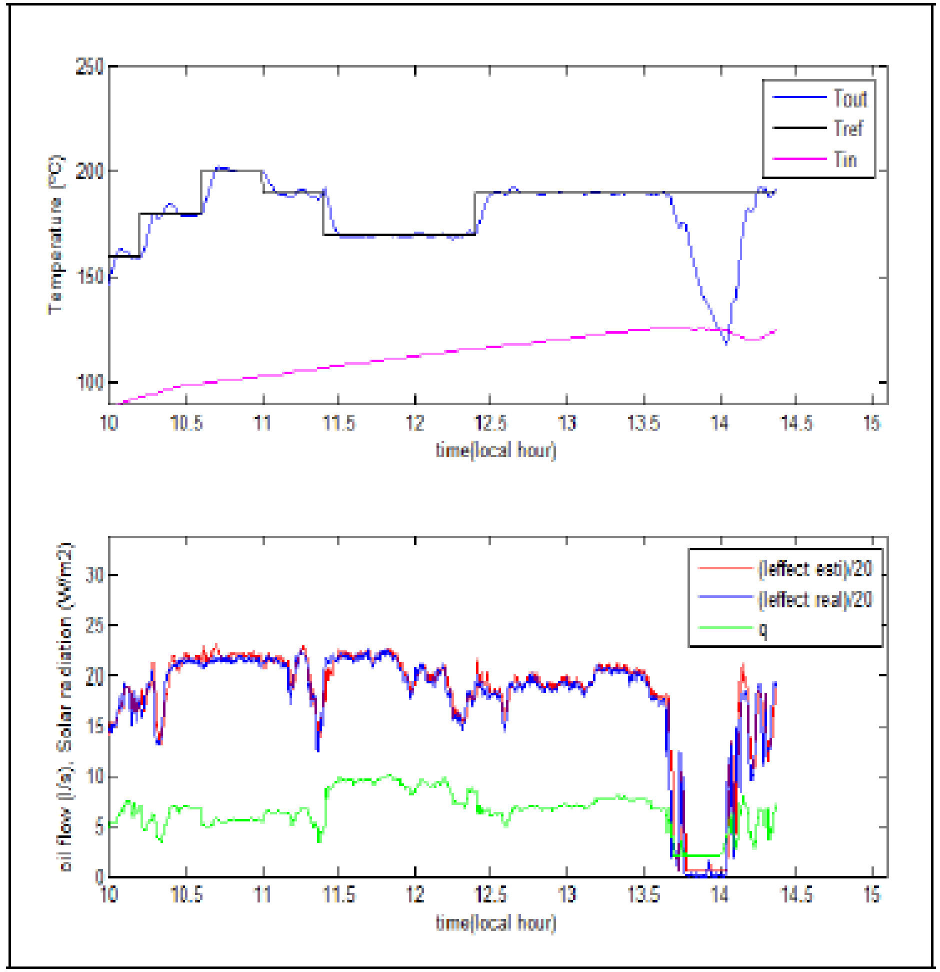
Non linear MPC (NMPC)

Non linear (non necessarily convex) optimization problem much more difficult to solve.

PSA Acurex



(c) Dia claro con nubosidad al final del día



(d) Día con perturbaciones en la radiación

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Atlantica Yield Trough Plants

Spain (650 MWe)

- Solucar (3x50MWe)
- Helioenergy (2x50MWe)
- Solacor (2x50MWe)
- Helios (2x50MWe)
- Solaben (4x50MWe)

USA (560 MWe)

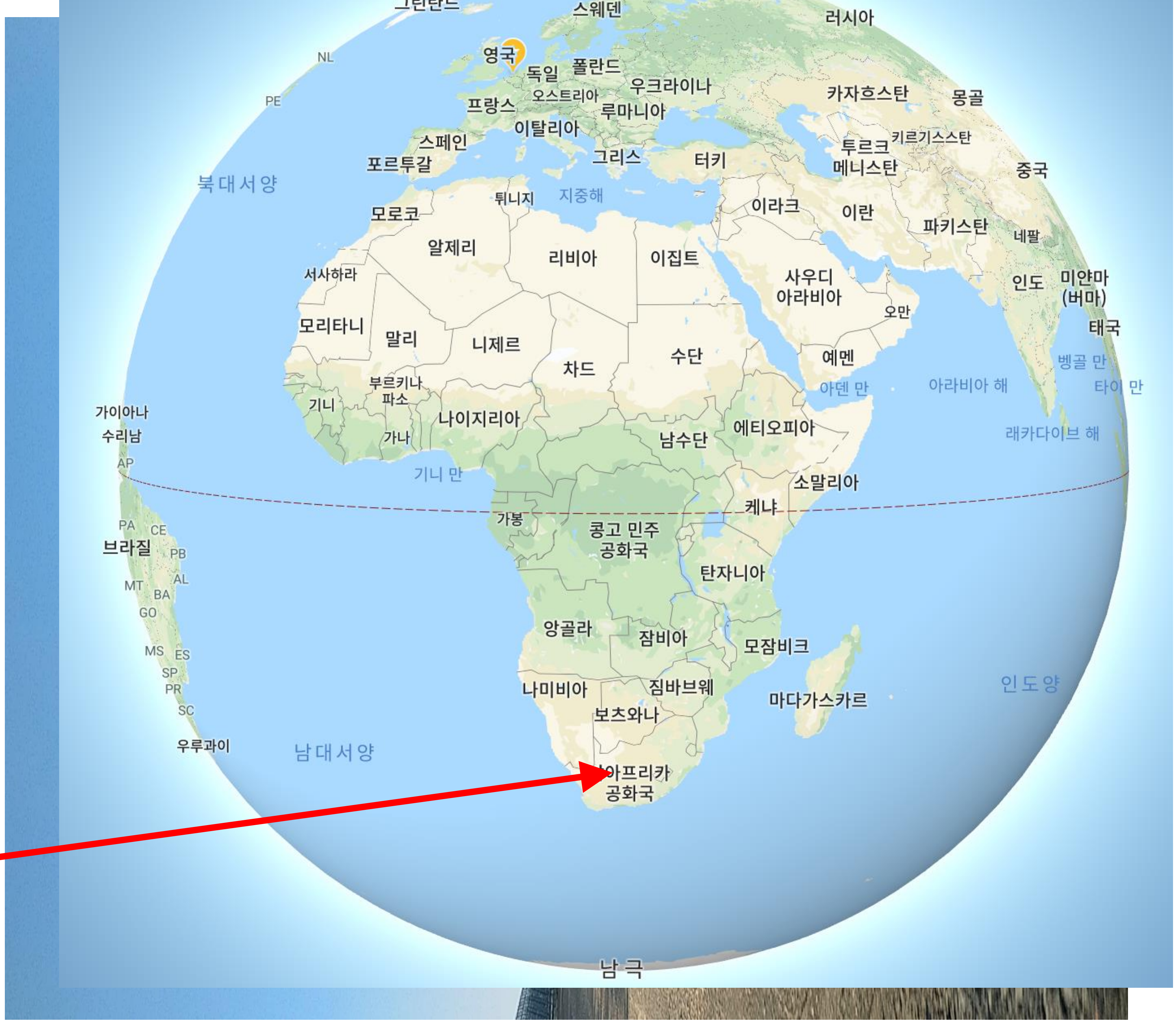
- Mojave (2x140 MWe)
- Solana (280 MWe)

South Africa

- Kaxu (100 MWe)

Solucar (3x50MWe)

Solucar (3x50MWe)


그린란드
스웨덴
러시아
NL
영국
독일
폴란드
PE
우크라이나
오스트리아
카자흐스탄
몽골
프랑스
루마니아
이탈리아
스페인
투르크
메니스탄
키르기스스탄
포르투갈
그리스
터키
중국
북대서양
튀니지
지중해
모로코
이라크
이란
파키스탄
네팔
알제리
리비아
이집트
서사하라
사우디
아라비아
인도
미얀마
(버마)
오만
모리타니
말리
니제르
태국
수단
예멘
차드
벵골 만
부르키나
파소
아덴 만
아라비아 해
타이 만
기니
가이아나
수리남
나이지리아
에티오피아
남수단
가나
래카다이브 해
AP
기니 만
소말리아
케냐
가봉
PA
CE
콩고 민주
공화국
브라질
PB
AL
탄자니아
MT
BA
GO
앙골라
잠비아
모잠비크
MS
ES
SP
PR
짐바브웨
나미비아
인도양
마다가스카르
SC
보츠와나
우루과이
남대서양
남아프리카
공화국
남극

Kaxu

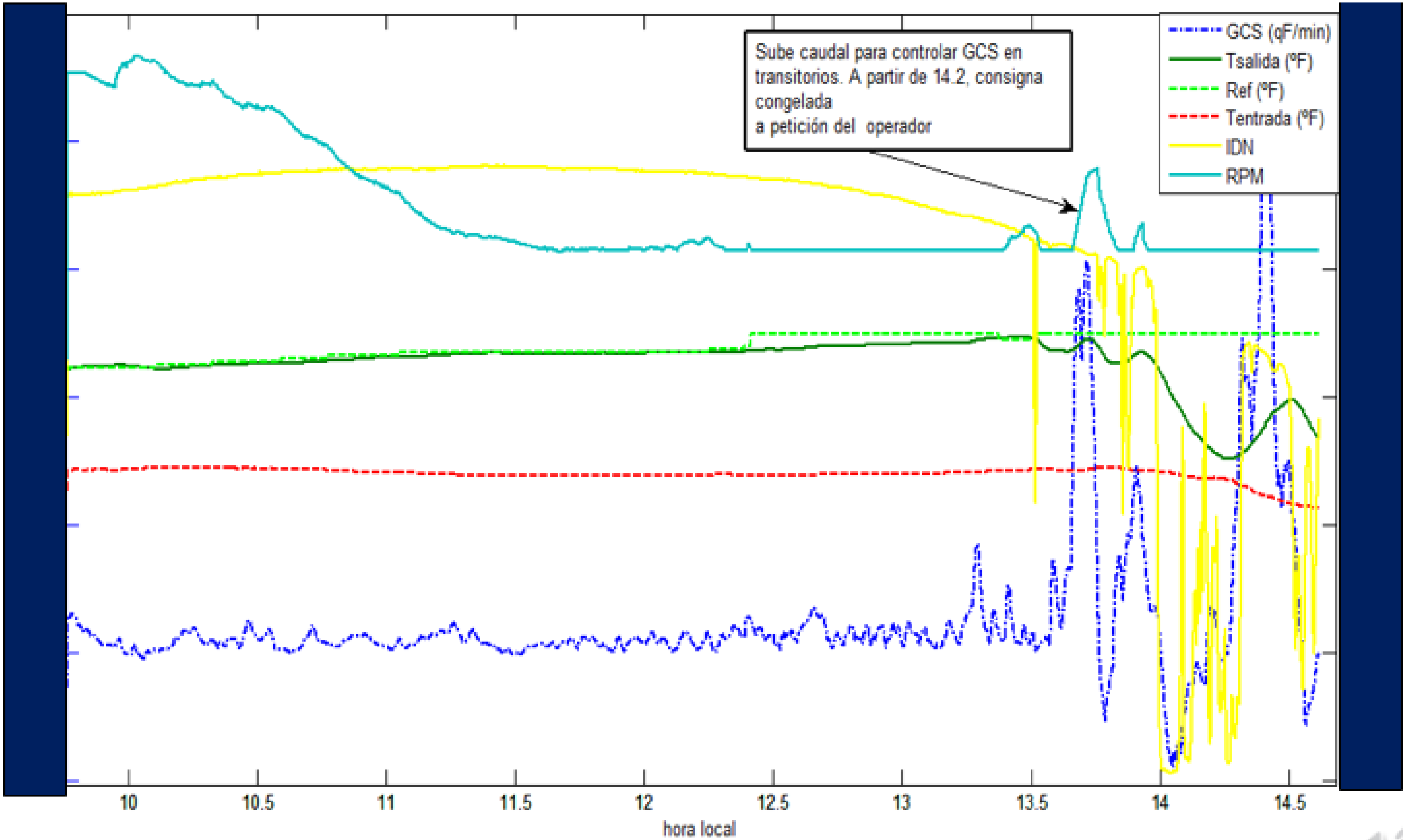
MPC application to real plants

- Solar field cannot be operated independently of steam generation system and turbines. It is necessary to take into account:
  - Steam pressure
  - HP valve aperture
  - Steam over-heating limitations
  - Power production limitations
  - Temperature gradients limitations
  - …
- Heuristic needed

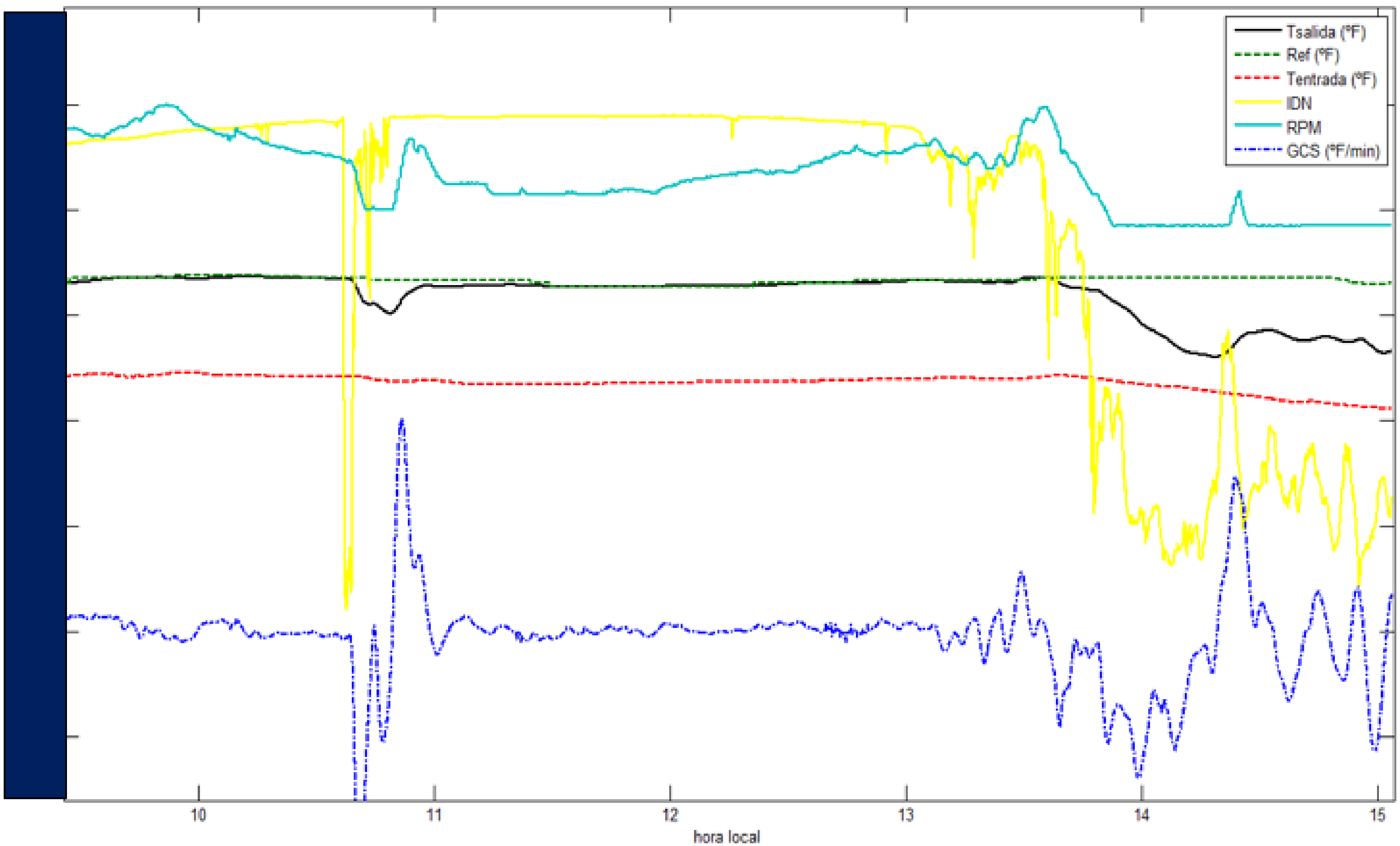
MPC application to real plants (Intelligence)

- We took some time in the control center of two 50 MW plants learning from experienced operators..
- We analized operator responses and searched for patterns.
- We translated patterns into a program

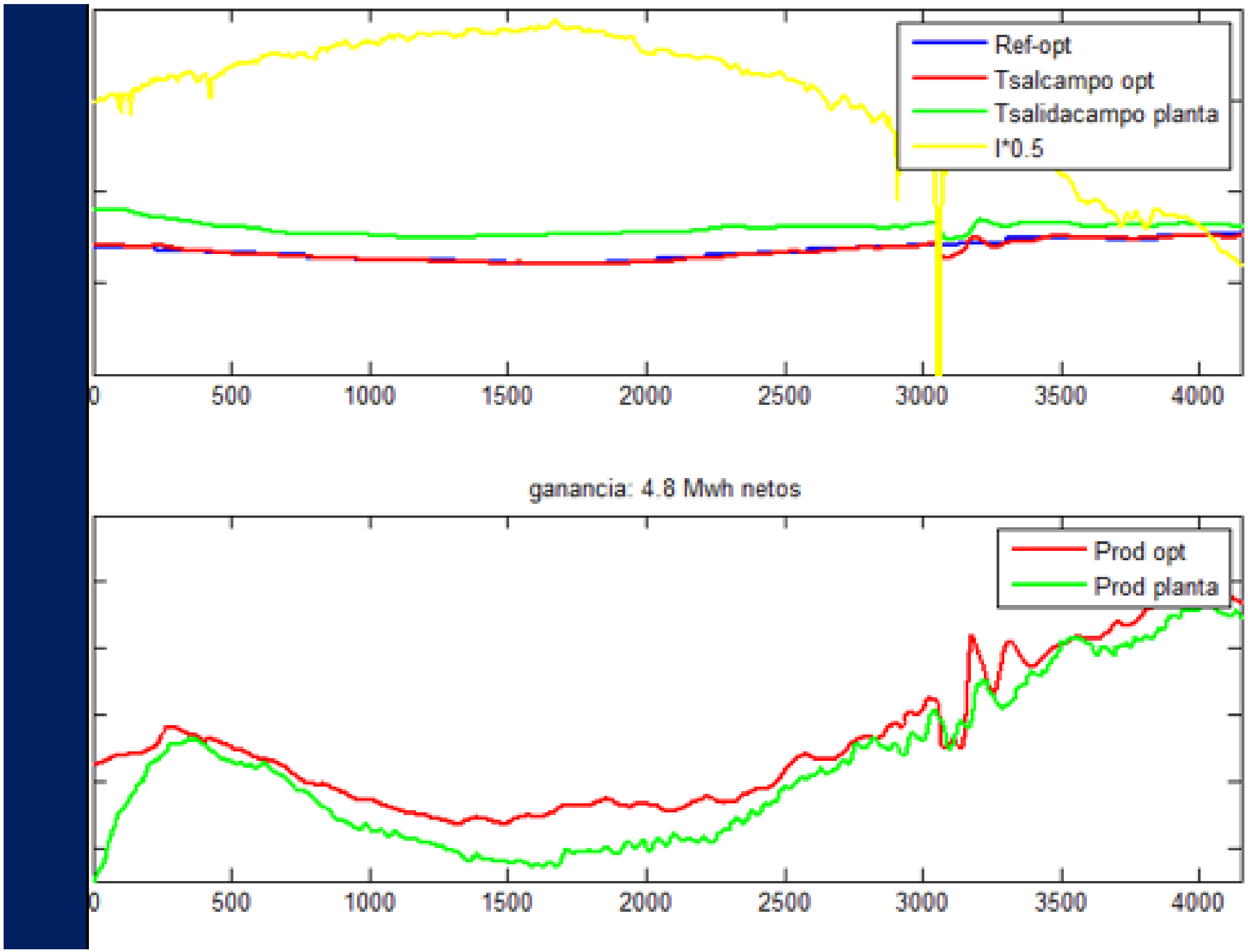
Level 3. Real plant results



Level 3. Real plant results



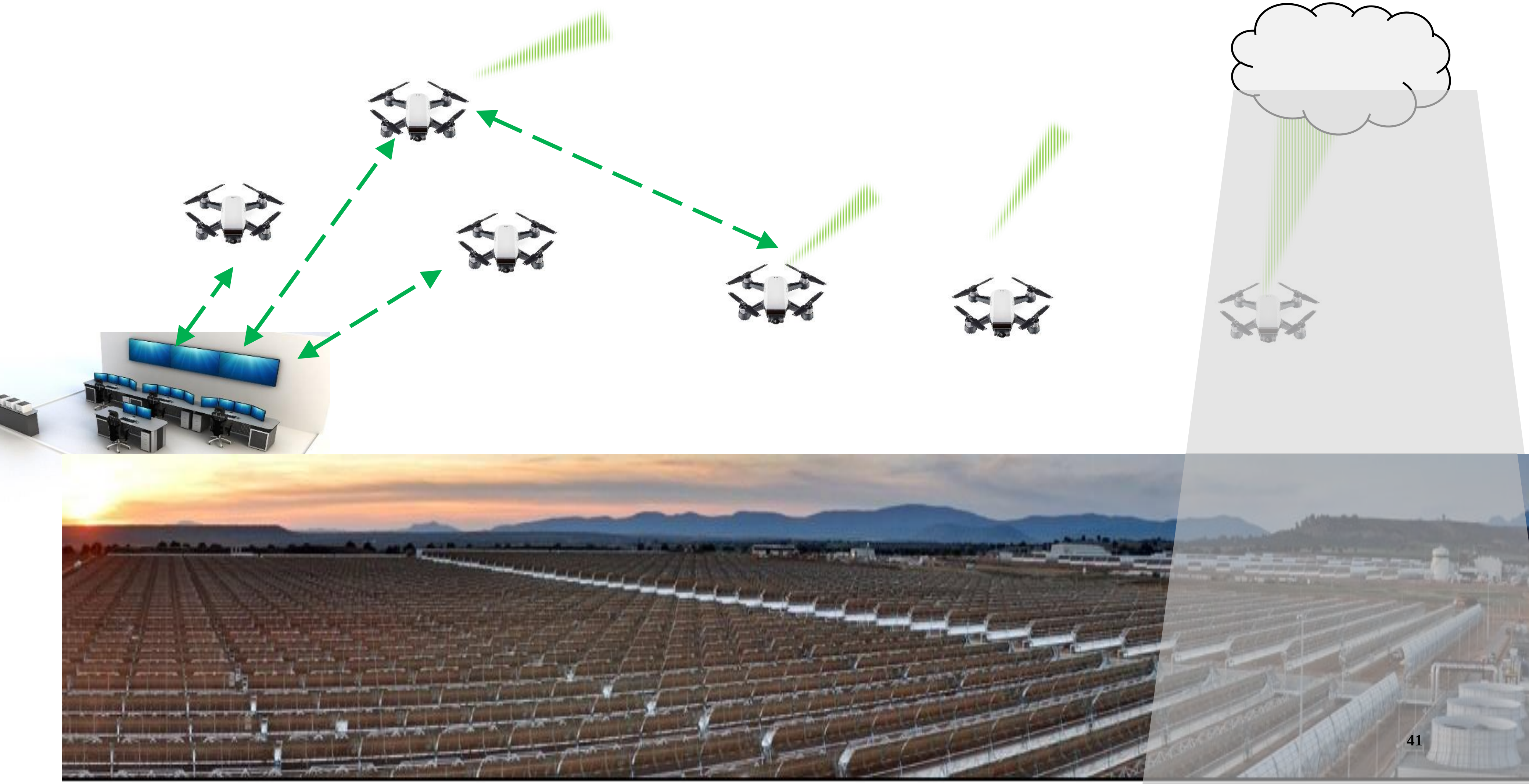
Level 2: Simulation vs a day operation.
A gain of 4.8 MWh (net) for a 50MW plant



Optimal Control of Thermal Solar Energy Systems

Advanced Research Grant European Research Council

Solar trough energy plants will be taken as case studies



Objectives

1. Methods to control mobile sensor fleets and integrate them as an essential part of the overall control systems.

2. Spatially distributed solar irradiance estimation methods using a variable fleet of sensors mounted on drones and UGVs.

3. New model predictive control (MPC) algorithms that use mobile solar sensor estimations and predictions to yield safer and more efficient operation

Conclusions

MPC controllers:

1. Always better than the best operator. Production increase between 0.5% and 2.5% depending of operator and day.
2. No constraint violations.
3. Production not relying in the operator skills.
4. Short pay-back periods

OCONTSOLAR:

1. Better control and supervision with better information
2. Initial studies have shown gains of around 4%.

Thanks

Some references

1. E.F. Camacho, M. Berenguer, F.R. Rubio and Diego Martínez, *Control of Solar Energy Systems*, Springer, 2012,

1. E.F. Camacho and C. Bordons, *Model Predictive Control*, Springer, 2007

efcamacho@us.es