Presentación del paradigma de modelado Energy Hub

Background:
ENERPRO Project (DPI2014-56364-C2-1-R)

Energy Management Strategies in Production Environments with Support of Solar Energy

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Content summary:

Motivation

Modelling an EH

Optimization results

Extending the model and further applications

Motivation

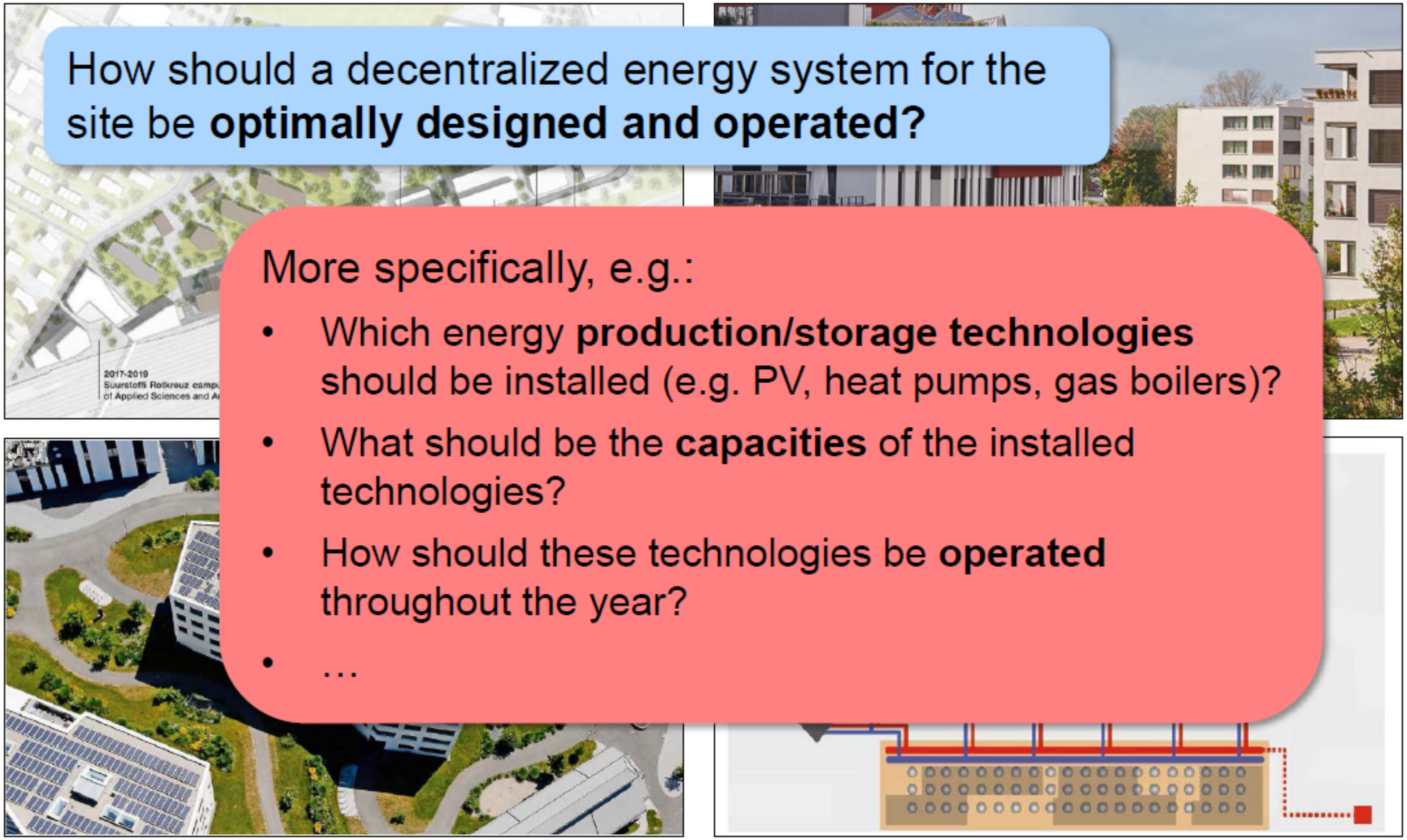
Problem

For a given **urban area/district/community**…

How should a decentralized energy system for the site be **optimally designed and operated?**

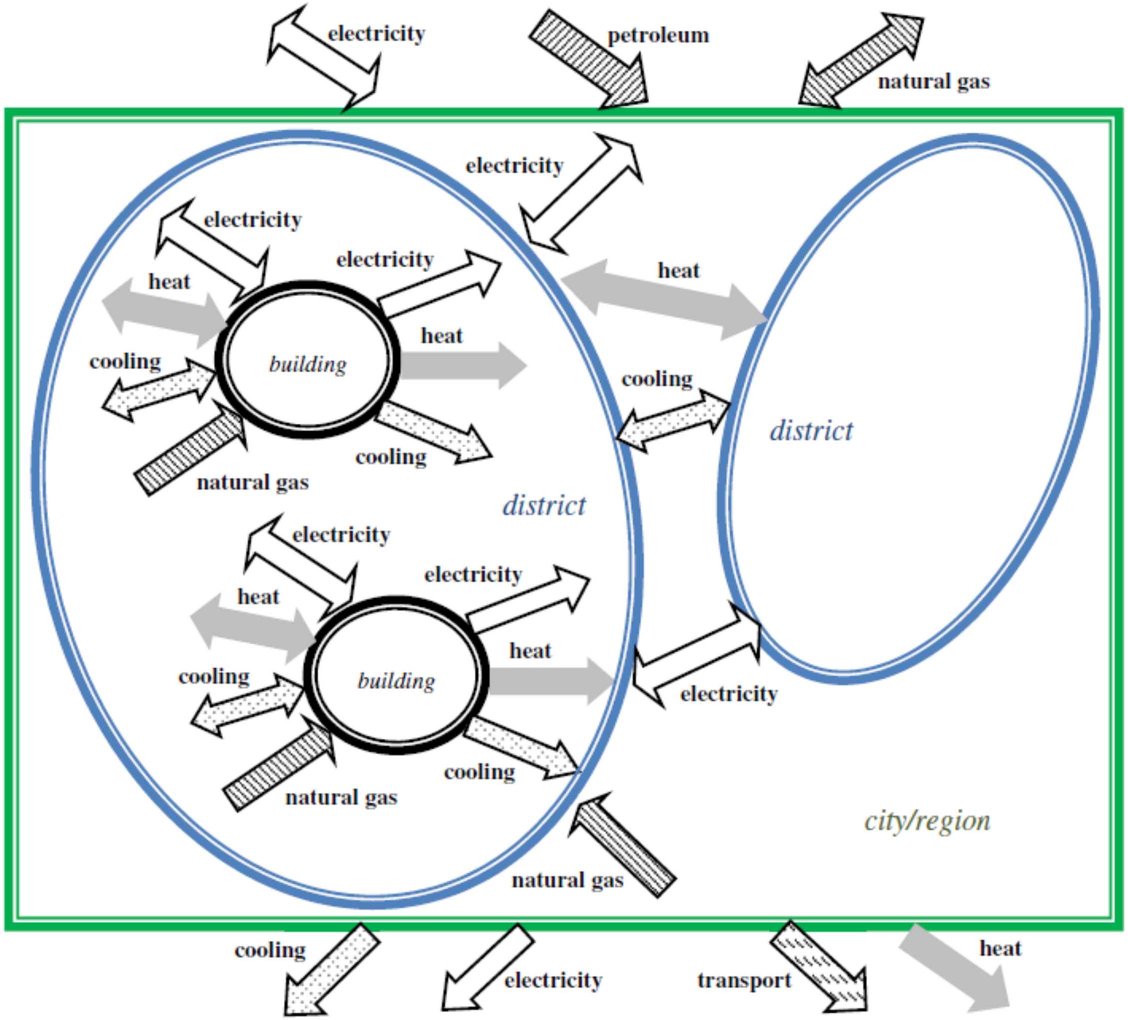
More specifically, e.g.:

- Which energy **production/storage technologies** should be installed (e.g. PV, heat pumps, gas boilers)?
- What should be the **capacities** of the installed technologies?
- How should these technologies be **operated** throughout the year?
- …



Suurstoffi Areal, Risch-Rotkreuz, Switzerland (image source: ZugEstates.ch, Suurstoffi.ch)

A multi-scale problem



- **How can the interactions between these scales be coordinated to improve overall energy performance?**
- Where should energy be produced/stored and in what quantities?
- How should transactions be coordinated?

Optimization

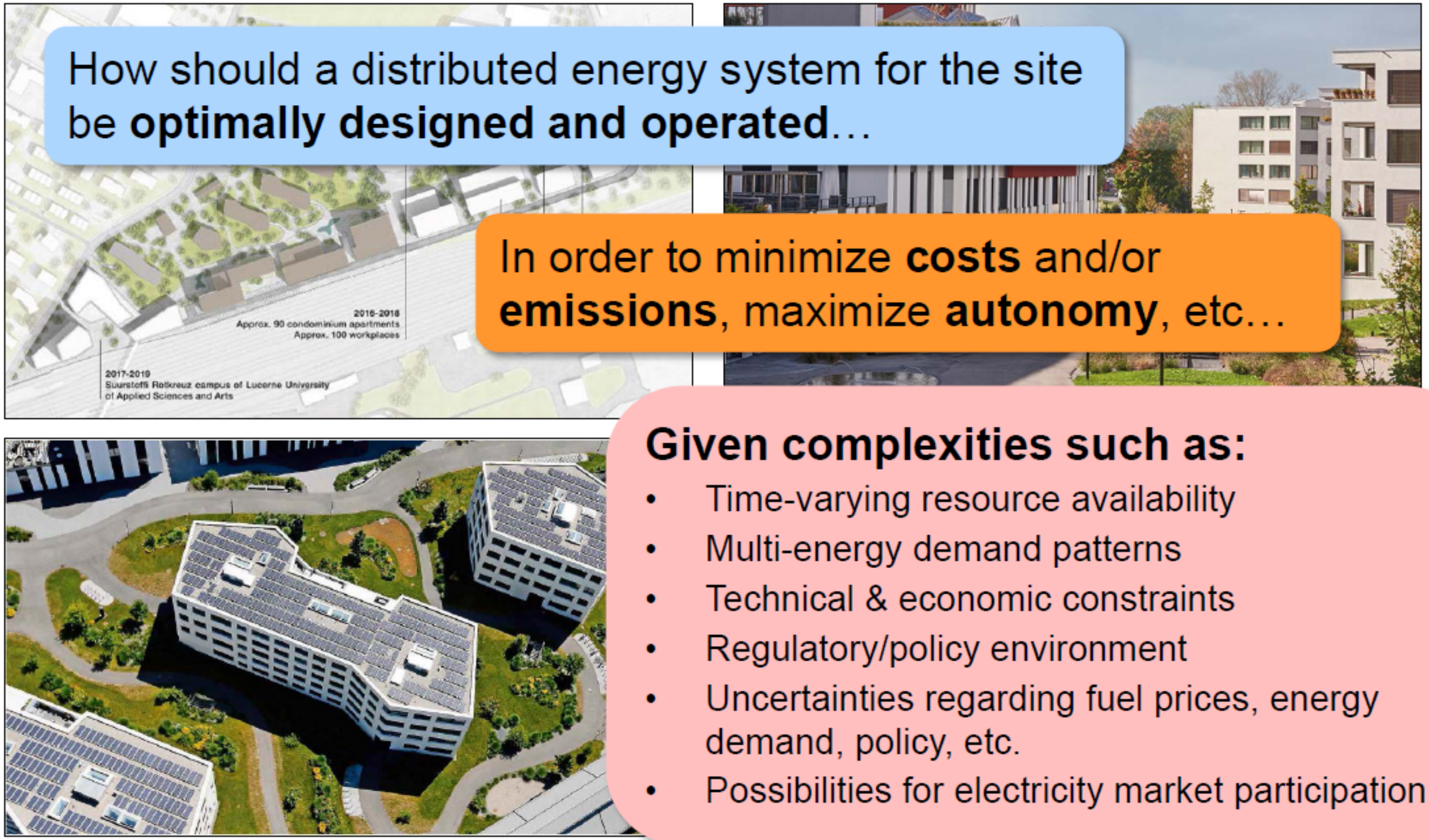
For a given **urban area/district/community**…

How should a distributed energy system for the site be **optimally designed and operated**…

In order to minimize **costs** and/or **emissions**, maximize **autonomy**, etc…

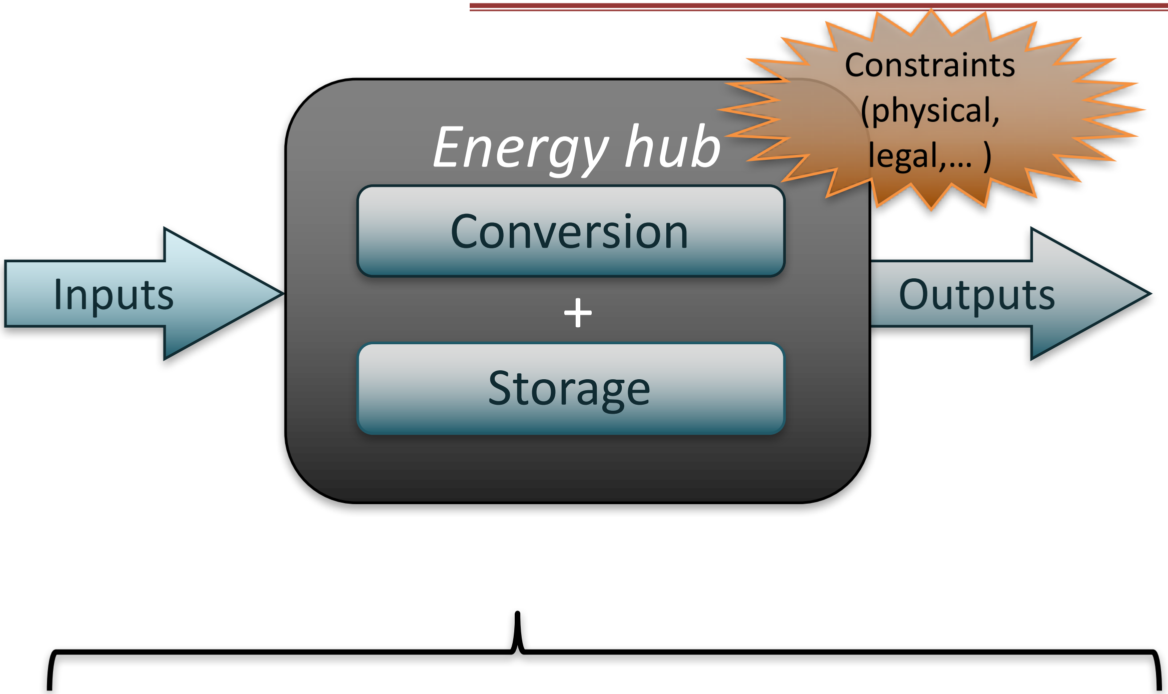
Given complexities such as:

- Time-varying resource availability
- Multi-energy demand patterns
- Technical & economic constraints
- Regulatory/policy environment
- Uncertainties regarding fuel prices, energy demand, policy, etc.
- Possibilities for electricity market participation



Suurstoffi Areal, Risch-Rotkreuz, Switzerland (image source: ZugEstates.ch, Suurstoffi.ch)

The energy hub concept



$$\boldsymbol{O}(k) = \boldsymbol{C}(k) \cdot \boldsymbol{I}(k) - \boldsymbol{Q}_c(k) + \boldsymbol{Q}_d(k)$$

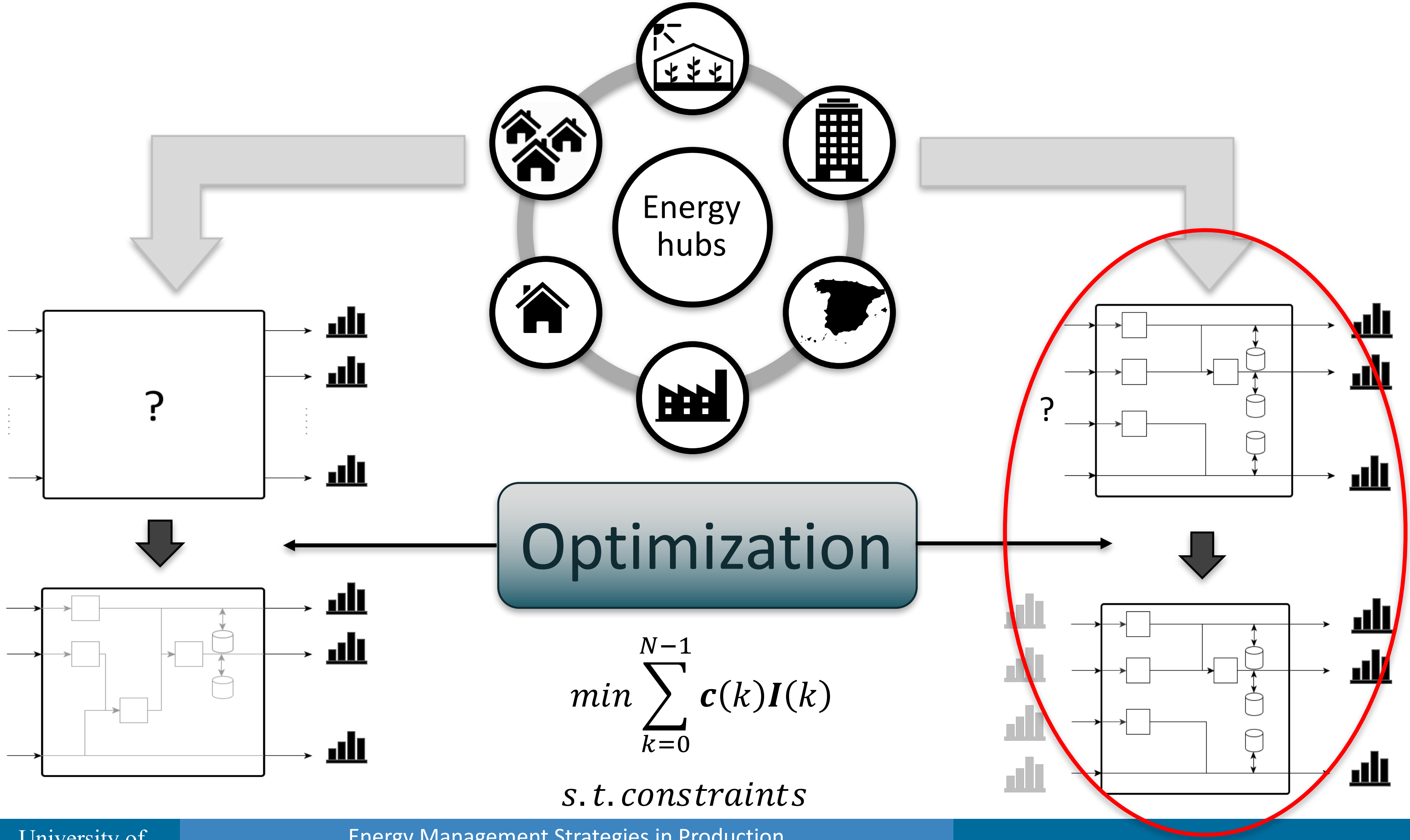
$$\boldsymbol{S}(k+1) = \boldsymbol{S}(k) + \boldsymbol{P}_c(k)\boldsymbol{Q}_c(k) - \boldsymbol{P}_d(k)\boldsymbol{Q}_d(k) - \boldsymbol{L}(k)\boldsymbol{S}(k)$$

$$\boldsymbol{I}^{mín}(k) \leq \boldsymbol{I}(k) \leq \boldsymbol{I}^{máx}(k) \qquad 0 \leq \boldsymbol{S}(k) \leq \boldsymbol{S}^{max}(k)$$

$$0 \leq \boldsymbol{Q}_c(k) \leq \boldsymbol{Q}_c^{max}(k) \qquad 0 \leq \boldsymbol{Q}_d(k) \leq \boldsymbol{Q}_d^{max}(k)$$

- Wide applicability concept
- Systems including energy or material resources
- Usually simplified models for optimizartion (↓computational burden)
- Certain variables can be controlled, and others cannot

The energy hub concept

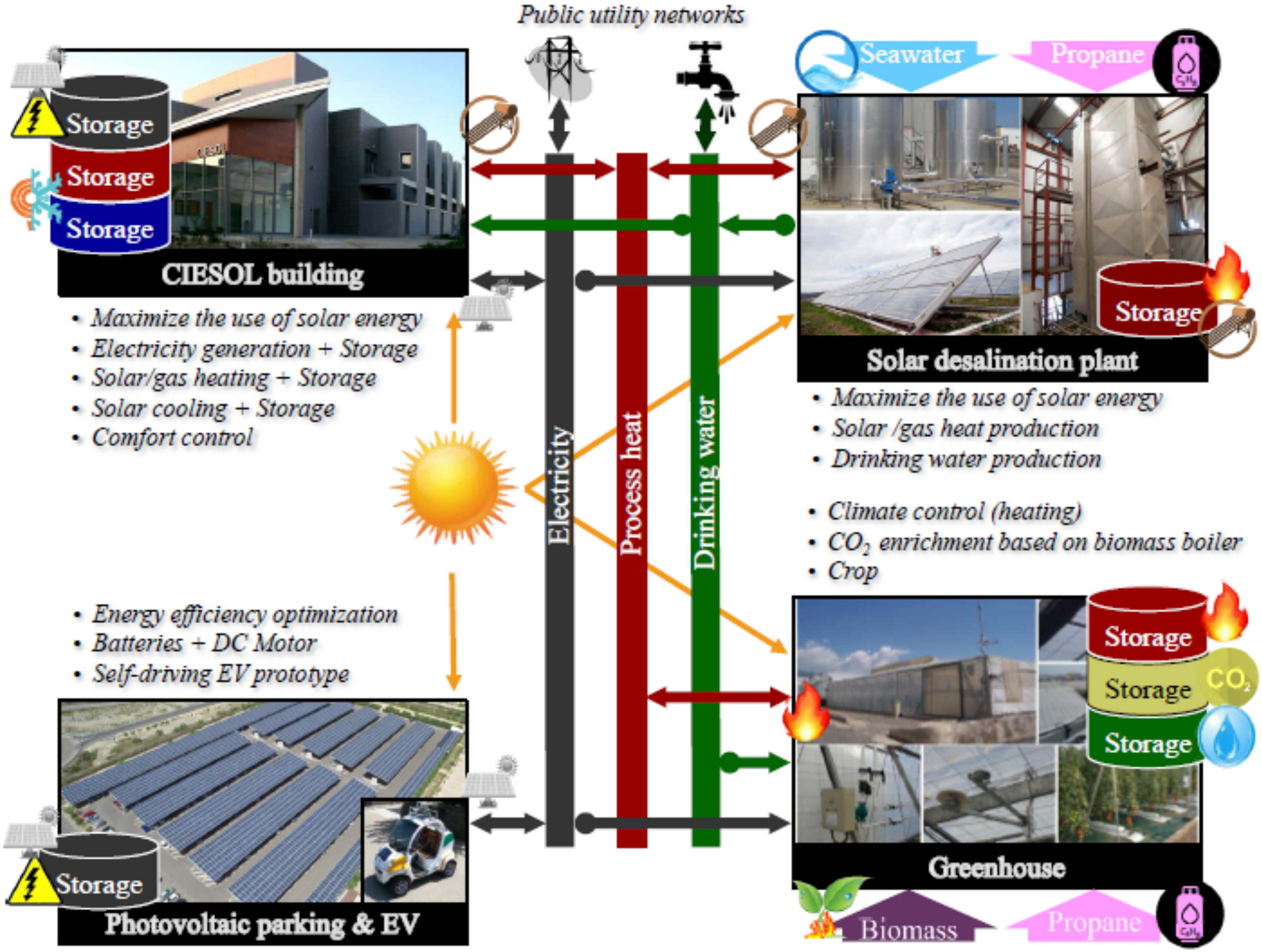


$$min \sum_{k=0}^{N-1} \boldsymbol{c}(k)\boldsymbol{I}(k)$$

$$s.t. constraints$$

Modelling an EH

ENERPRO Plant



- Self-sustaining test-bed plant consisting of four sub-systems
- Development of coordination, management and control strategies
- Available data of each facility between 2013 and 2017 on a minute basis

ENERPRO Plant

⚡ 🔥 ❄ 💧

- Photovoltaic field ⚡
- Solar collectors field 🔥
- Absorption chiller ❄
- Reversible heat pump ❄ 🔥

- Photovoltaic field ⚡

ENERPRO Plant

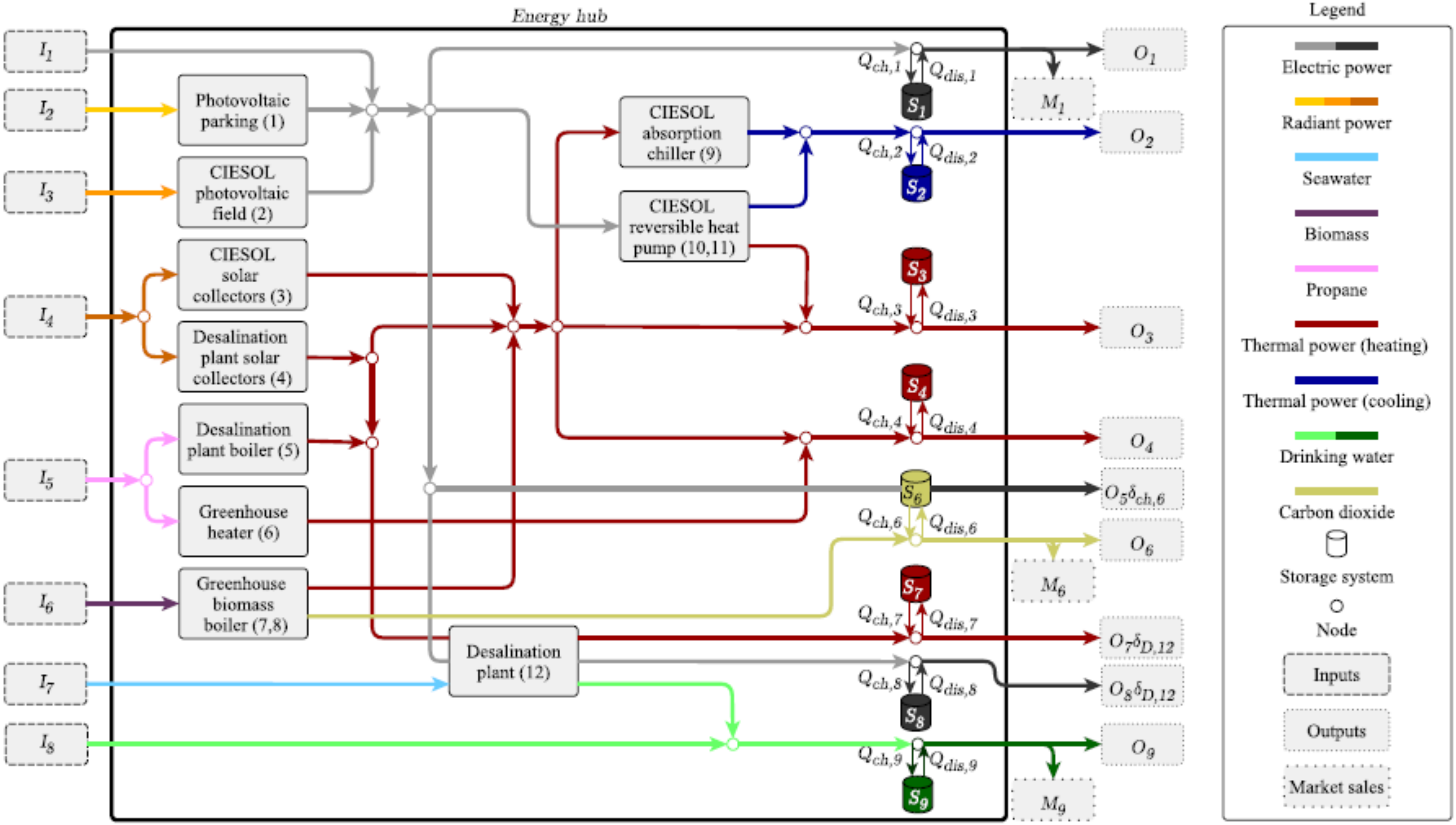
- Desalination module 💧
- Solar collectors field 🔥
- Propane boiler 🔥

🔥

- Biomass boiler 🔥 CO_2
- Propane heater 🔥

🔥 💧 CO_2

Modelling



Inputs: $i = 1, \dots, 8$ Outputs: $o = 1, \dots, 9$ Devices: $d = 1, \dots, 12$ Paths: $p = 1, \dots, 30$

Modelling

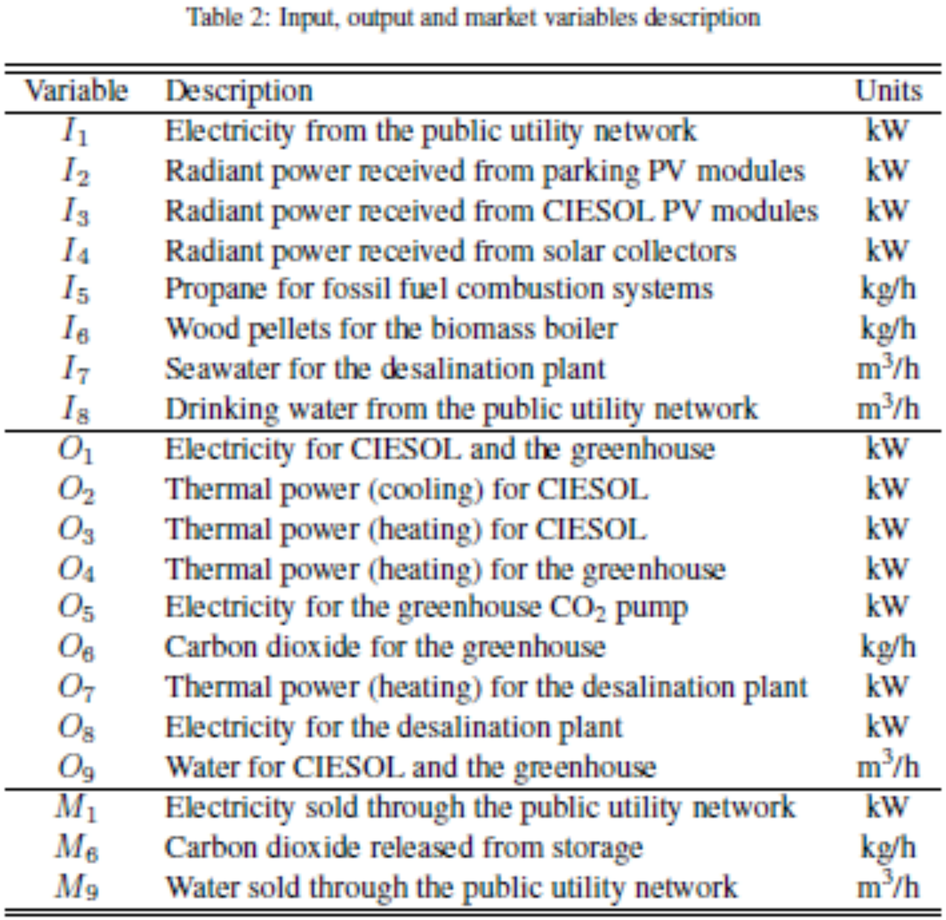


Table 2: Input, output and market variables description

Variable	Description	Units
I_1	Electricity from the public utility network	kW
I_2	Radiant power received from parking PV modules	kW
I_3	Radiant power received from CIESOL PV modules	kW
I_4	Radiant power received from solar collectors	kW
I_5	Propane for fossil fuel combustion systems	kg/h
I_6	Wood pellets for the biomass boiler	kg/h
I_7	Seawater for the desalination plant	m^3/h
I_8	Drinking water from the public utility network	m^3/h
O_1	Electricity for CIESOL and the greenhouse	kW
O_2	Thermal power (cooling) for CIESOL	kW
O_3	Thermal power (heating) for CIESOL	kW
O_4	Thermal power (heating) for the greenhouse	kW
O_5	Electricity for the greenhouse CO_2 pump	kW
O_6	Carbon dioxide for the greenhouse	kg/h
O_7	Thermal power (heating) for the desalination plant	kW
O_8	Electricity for the desalination plant	kW
O_9	Water for CIESOL and the greenhouse	m^3/h
M_1	Electricity sold through the public utility network	kW
M_6	Carbon dioxide released from storage	kg/h
M_9	Water sold through the public utility network	m^3/h

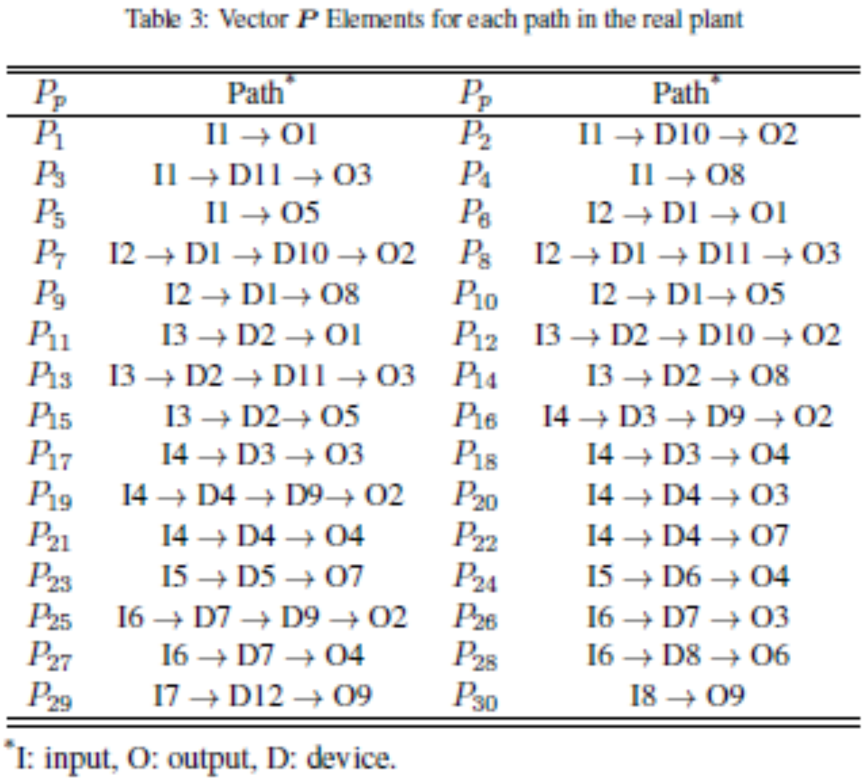


Table 3: Vector $\boldsymbol{P}$ Elements for each path in the real plant

P_p	Path*	P_p	Path*
P_1	I1 → O1	P_2	I1 → D10 → O2
P_3	I1 → D11 → O3	P_4	I1 → O8
P_5	I1 → O5	P_6	I2 → D1 → O1
P_7	I2 → D1 → D10 → O2	P_8	I2 → D1 → D11 → O3
P_9	I2 → D1→ O8	P_{10}	I2 → D1→ O5
P_{11}	I3 → D2 → O1	P_{12}	I3 → D2 → D10 → O2
P_{13}	I3 → D2 → D11 → O3	P_{14}	I3 → D2 → O8
P_{15}	I3 → D2→ O5	P_{16}	I4 → D3 → D9 → O2
P_{17}	I4 → D3 → O3	P_{18}	I4 → D3 → O4
P_{19}	I4 → D4 → D9→ O2	P_{20}	I4 → D4 → O3
P_{21}	I4 → D4 → O4	P_{22}	I4 → D4 → O7
P_{23}	I5 → D5 → O7	P_{24}	I5 → D6 → O4
P_{25}	I6 → D7 → D9 → O2	P_{26}	I6 → D7 → O3
P_{27}	I6 → D7 → O4	P_{28}	I6 → D8 → O6
P_{29}	I7 → D12 → O9	P_{30}	I8 → O9

*I: input, O: output, D: device.

Modelling

Conversion model $\boldsymbol{\delta_O(k)O(k)+M(k)=C(k)P(k)-Q_{ch}(k)+Q_{dis}(k)}$

Storage model $\boldsymbol{S(k+1)=L(k)S(k)+C_{ch}(k)Q_{ch}(k)-C_{dis}(k)Q_{dis}(k)}$

Production limits: inputs, devices and sales $I_i^{min}(k)\delta_{I,i}(k) \leq I_i(k) \leq I_i^{max}(k)\delta_{I,i}(k),$

$\boldsymbol{I(k)=C_iP(k)}$

$$M_o^{min}(k)\delta_{M,o}(k) \leq M_o(k) \leq M_o^{max}(k)\delta_{M,o}(k),$$

$\boldsymbol{D(k)=C_d(k)P(k)}$

$$D_d^{min}(k)\delta_{D,d}(k) \leq D_d(k) \leq D_d^{max}(k)\delta_{D,d}(k),$$

Storage limits

$$Q_{ch,o}^{min}(k)\delta_{ch,o}(k) \leq Q_{ch,o}(k) \leq Q_{ch,o}^{max}(k)\delta_{ch,o}(k),$$

$$Q_{dis,o}^{min}(k)\delta_{dis,o}(k) \leq Q_{dis,o}(k) \leq Q_{dis,o}^{max}(k)\delta_{dis,o}(k),$$

$$S_o^{min}(k) \leq S_o(k) \leq S_o^{max}(k),$$

Non-simultaneous processes

$$\delta_{ch,o}(k)+\delta_{dis,o}(k) \leq 1$$

$$\delta_{I,1}(k)+\delta_{M,1}(k) \leq 1$$

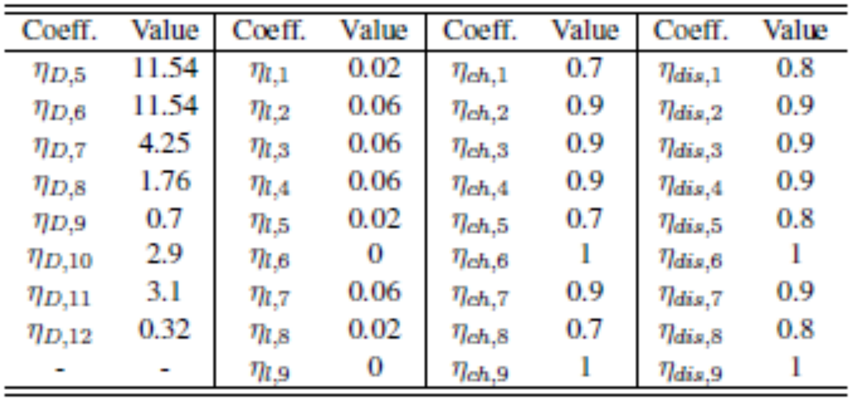
$$\delta_{I,8}(k)+\delta_{M,9}(k) \leq 1$$

$$\delta_{D,10}(k)+\delta_{D,11}(k) \leq 1$$

$$P_{25}+P_{26}+P_{27}=P_{28}$$

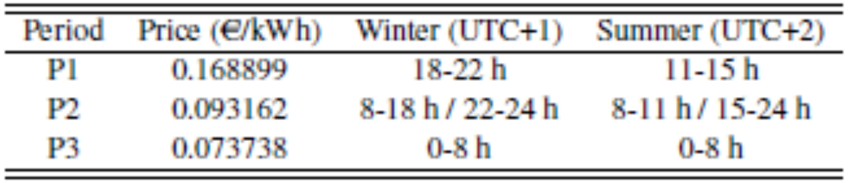
Modelling

Table 5: Conversion, degradation, charge and discharge coefficients



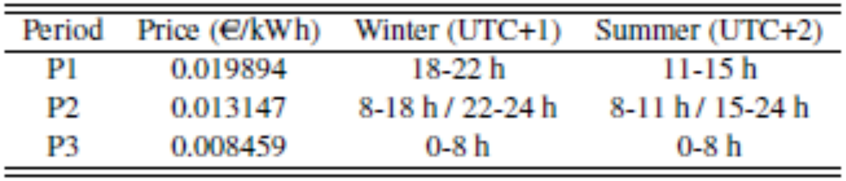
Coeff.	Value	Coeff.	Value	Coeff.	Value	Coeff.	Value
$\eta_{D,5}$	11.54	$\eta_{l,1}$	0.02	$\eta_{ch,1}$	0.7	$\eta_{dis,1}$	0.8
$\eta_{D,6}$	11.54	$\eta_{l,2}$	0.06	$\eta_{ch,2}$	0.9	$\eta_{dis,2}$	0.9
$\eta_{D,7}$	4.25	$\eta_{l,3}$	0.06	$\eta_{ch,3}$	0.9	$\eta_{dis,3}$	0.9
$\eta_{D,8}$	1.76	$\eta_{l,4}$	0.06	$\eta_{ch,4}$	0.9	$\eta_{dis,4}$	0.9
$\eta_{D,9}$	0.7	$\eta_{l,5}$	0.02	$\eta_{ch,5}$	0.7	$\eta_{dis,5}$	0.8
$\eta_{D,10}$	2.9	$\eta_{l,6}$	0	$\eta_{ch,6}$	1	$\eta_{dis,6}$	1
$\eta_{D,11}$	3.1	$\eta_{l,7}$	0.06	$\eta_{ch,7}$	0.9	$\eta_{dis,7}$	0.9
$\eta_{D,12}$	0.32	$\eta_{l,8}$	0.02	$\eta_{ch,8}$	0.7	$\eta_{dis,8}$	0.8
-	-	$\eta_{l,9}$	0	$\eta_{ch,9}$	1	$\eta_{dis,9}$	1

Table 6: Local supply company tariff prices (p_E) [47]



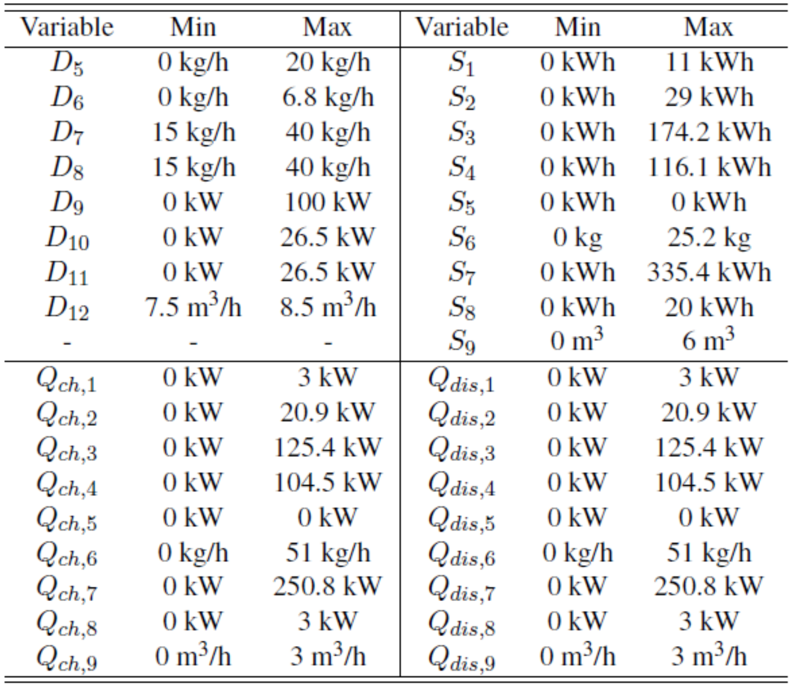
Period	Price (€/kWh)	Winter (UTC+1)	Summer (UTC+2)
P1	0.168899	18-22 h	11-15 h
P2	0.093162	8-18 h / 22-24 h	8-11 h / 15-24 h
P3	0.073738	0-8 h	0-8 h

Table 7: Variable charges with the 3.0A access fee (p_{PV}) [38]



Period	Price (€/kWh)	Winter (UTC+1)	Summer (UTC+2)
P1	0.019894	18-22 h	11-15 h
P2	0.013147	8-18 h / 22-24 h	8-11 h / 15-24 h
P3	0.008459	0-8 h	0-8 h

Table 4: Upper and lower limits for converters, storage capacity, charge and discharge flows



Variable	Min	Max	Variable	Min	Max
D_5	0 kg/h	20 kg/h	S_1	0 kWh	11 kWh
D_6	0 kg/h	6.8 kg/h	S_2	0 kWh	29 kWh
D_7	15 kg/h	40 kg/h	S_3	0 kWh	174.2 kWh
D_8	15 kg/h	40 kg/h	S_4	0 kWh	116.1 kWh
D_9	0 kW	100 kW	S_5	0 kWh	0 kWh
D_{10}	0 kW	26.5 kW	S_6	0 kg	25.2 kg
D_{11}	0 kW	26.5 kW	S_7	0 kWh	335.4 kWh
D_{12}	7.5 m^3/h	8.5 m^3/h	S_8	0 kWh	20 kWh
-	-	-	S_9	0 m^3	6 m^3
$Q_{ch,1}$	0 kW	3 kW	$Q_{dis,1}$	0 kW	3 kW
$Q_{ch,2}$	0 kW	20.9 kW	$Q_{dis,2}$	0 kW	20.9 kW
$Q_{ch,3}$	0 kW	125.4 kW	$Q_{dis,3}$	0 kW	125.4 kW
$Q_{ch,4}$	0 kW	104.5 kW	$Q_{dis,4}$	0 kW	104.5 kW
$Q_{ch,5}$	0 kW	0 kW	$Q_{dis,5}$	0 kW	0 kW
$Q_{ch,6}$	0 kg/h	51 kg/h	$Q_{dis,6}$	0 kg/h	51 kg/h
$Q_{ch,7}$	0 kW	250.8 kW	$Q_{dis,7}$	0 kW	250.8 kW
$Q_{ch,8}$	0 kW	3 kW	$Q_{dis,8}$	0 kW	3 kW
$Q_{ch,9}$	0 m^3/h	3 m^3/h	$Q_{dis,9}$	0 m^3/h	3 m^3/h

$$\mathbf{c}(k) = \begin{bmatrix} c_1 & c_2 & c_3 & 0 & c_5 & c_6 & 0 & c_8 \end{bmatrix}$$

$$\mathbf{s}(k) = \begin{bmatrix} s_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & s_9 \end{bmatrix}$$

$$\boxed{\eta_{SC} = \frac{Q_u}{G_T A_{c,T}} = \frac{\dot{m}_f}{\dot{m}_{eq}}\left(\frac{L_{eq}\beta_r}{A_{c,T}} - \frac{h_{SC}\left(T_{sc,m} - T_a\right)}{G_T A_{c,T}}\right)}$$

PV Modelling

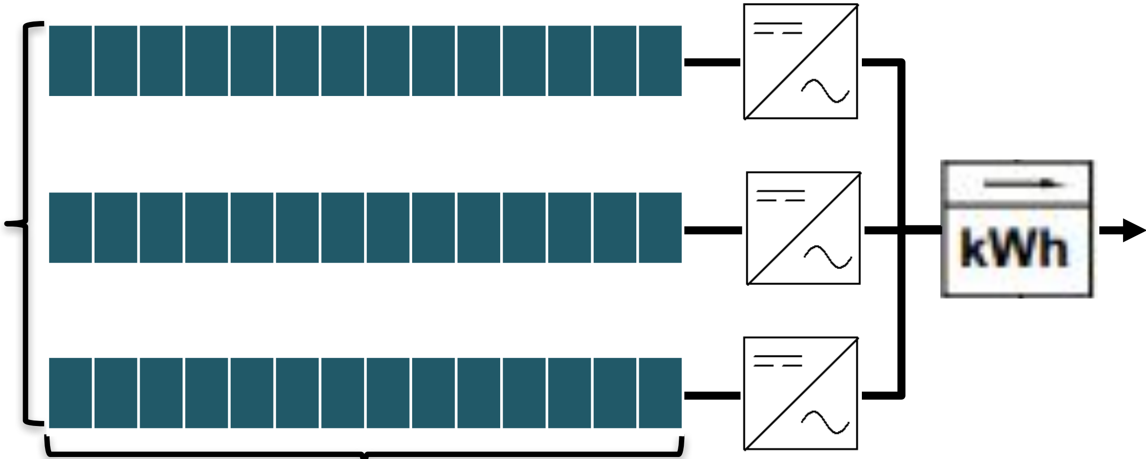
PV facility model

Global performance of the field (η) → $C(k)$

Available radiation on sloped surface ($G_T \cdot A$) → $I^{máx}(k)$

Total PV array area

CIESOL PV field



42 Atersa A-222P modules

14 series modules per inverter

3 CICLO-3000 inverters

Measurements:

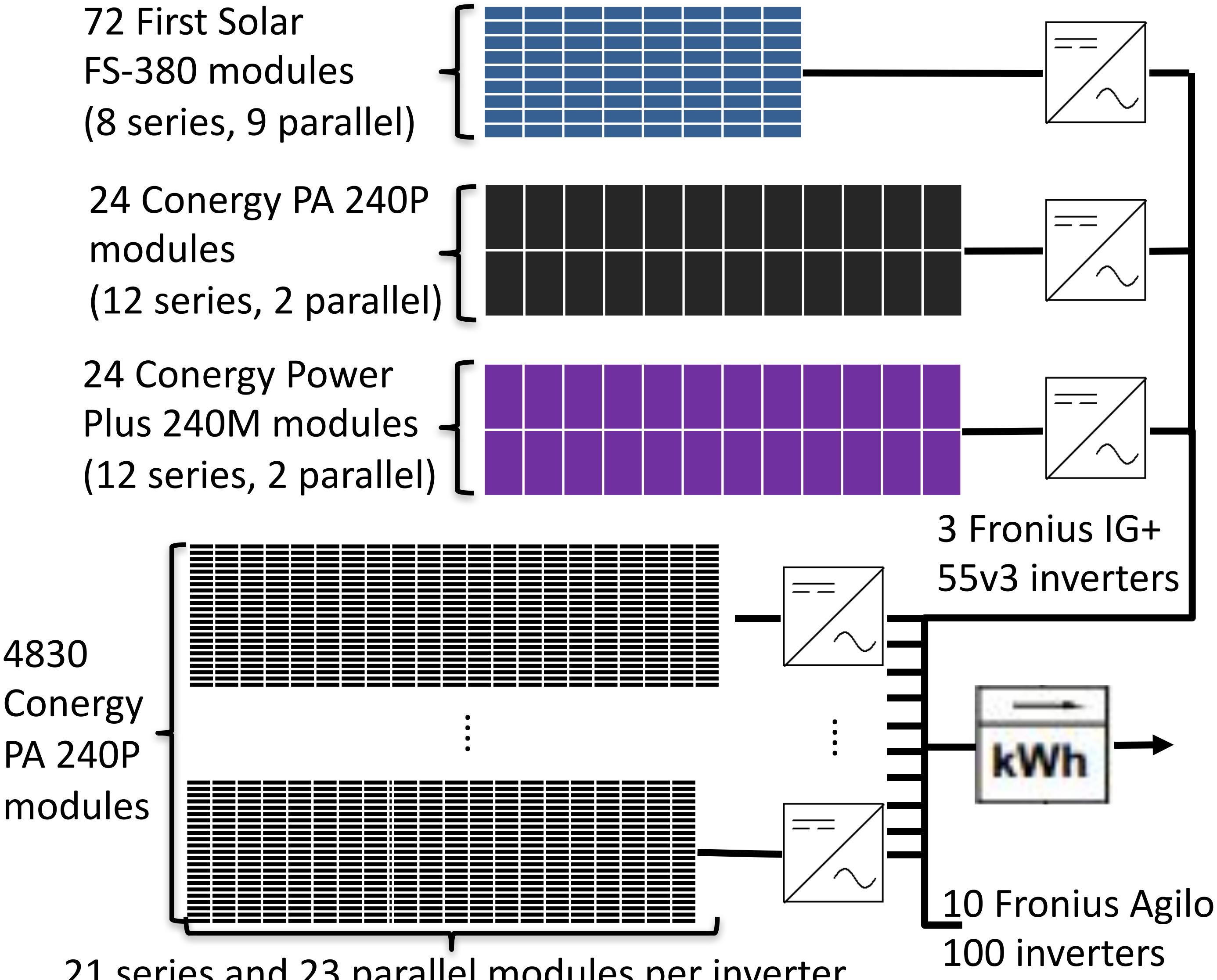
- Every minute from 2013 to 2017
- Radiation and temperature
- Detailed inverters I/O

PV Modelling

Parking PV field

Measurements:

- From 04/2013 to 03/2014
- Daily total production
- Monthly inverters production



72 First Solar FS-380 modules (8 series, 9 parallel)

24 Conergy PA 240P modules (12 series, 2 parallel)

24 Conergy Power Plus 240M modules (12 series, 2 parallel)

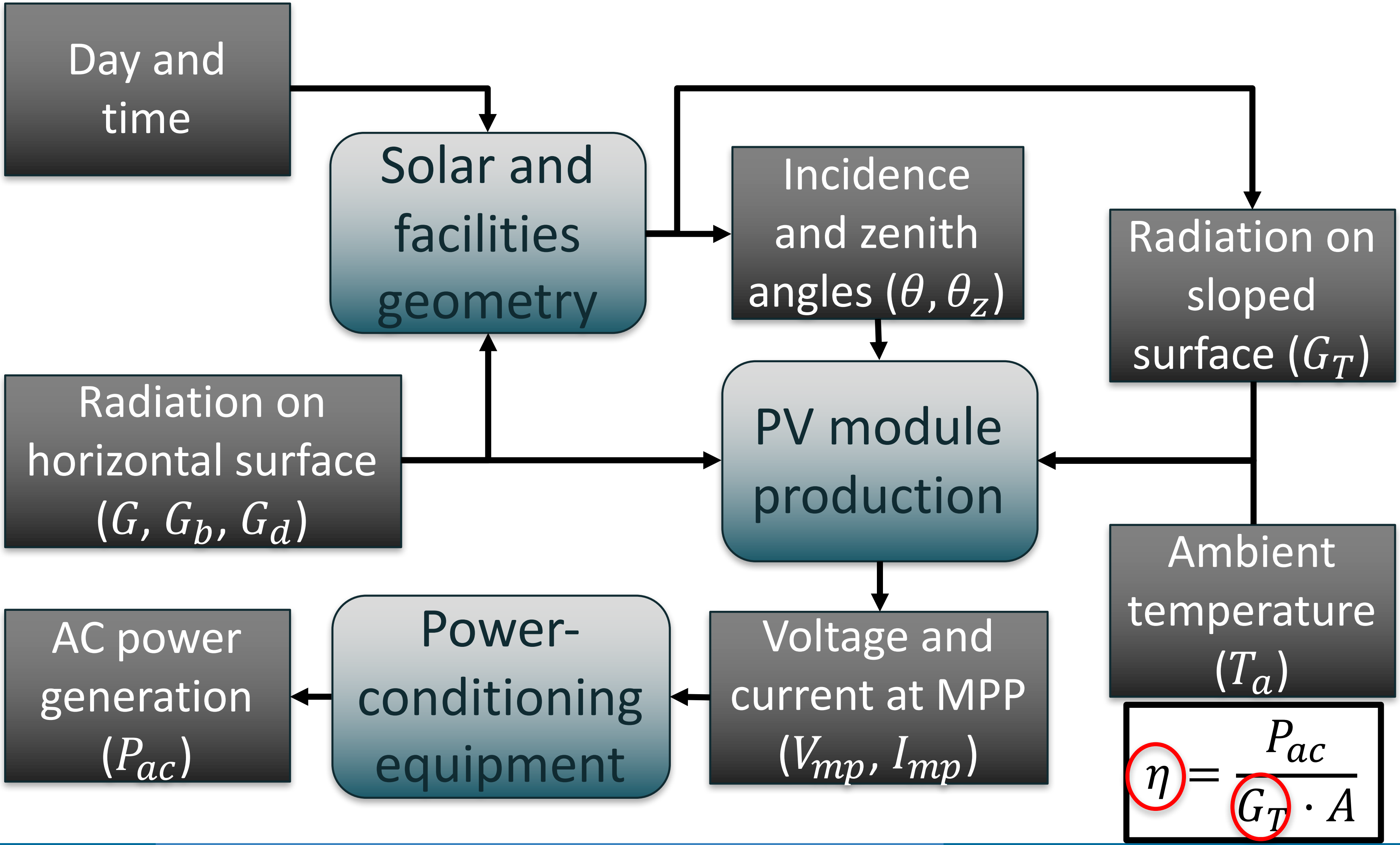
3 Fronius IG+ 55v3 inverters

4830 Conergy PA 240P modules

21 series and 23 parallel modules per inverter

10 Fronius Agilo 100 inverters

PV Modelling



Day and time

Solar and facilities geometry

Incidence and zenith angles (θ, θ_z)

Radiation on sloped surface (G_T)

Radiation on horizontal surface (G, G_b, G_d)

PV module production

Ambient temperature (T_a)

AC power generation (P_{ac})

Power-conditioning equipment

Voltage and current at MPP (V_{mp}, I_{mp})

$$\eta = \frac{P_{ac}}{G_T \cdot A}$$

PV Modelling

Solar and facilities geometry

$$G_T = G_b R_b + G_d \frac{1+\cos\beta}{2} + (G_b + G_d)\rho_g \frac{1-\cos\beta}{2}$$

ρ_g ↓ Ground reflectance

R_b ↓

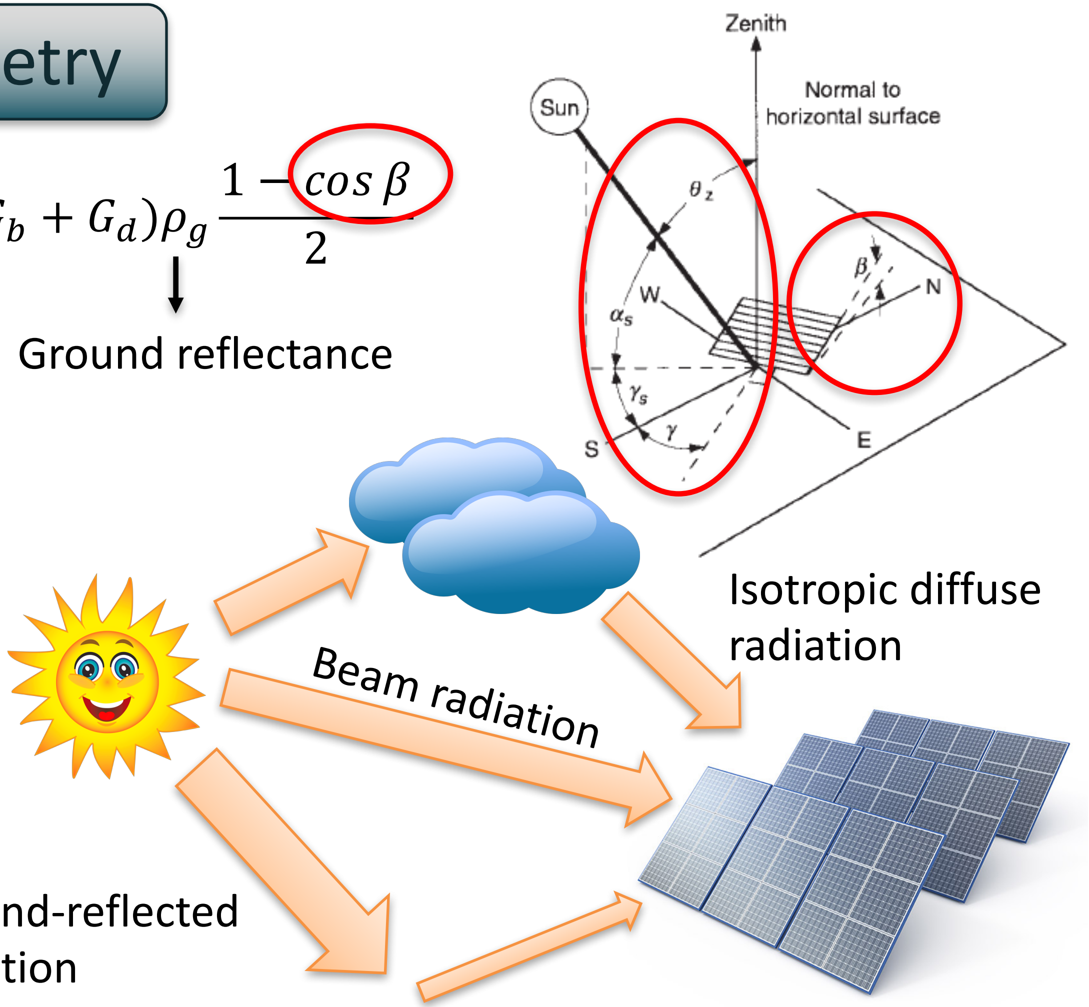
$$R_b = \frac{\cos\theta}{\cos\theta_z}$$

PV facilities angles:

- Slope (β)
- Latitude (ϕ)
- Azimut (γ)

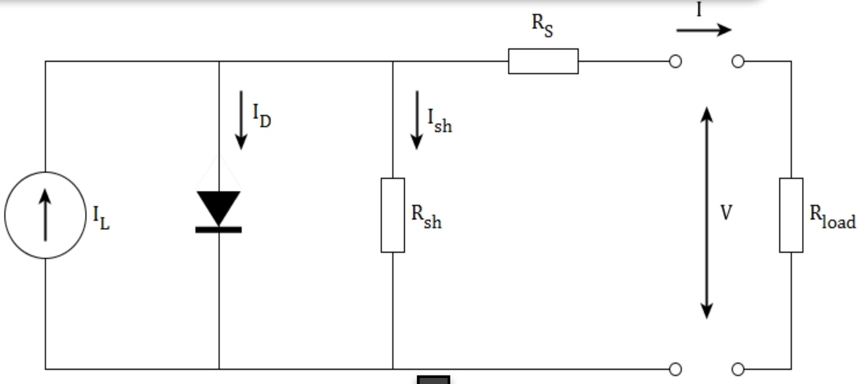
Solar angles:

- Declination (δ) ← Day
- Hour angle (ω) ← Time



PV Modelling

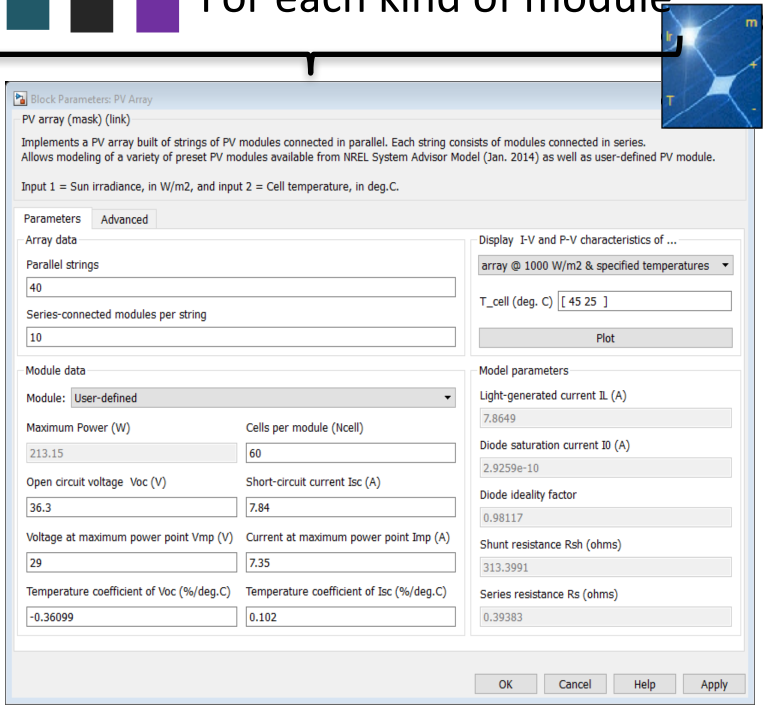
PV module production



$$I = I_L - I_o\left[e^{\left(\frac{V+IR_s}{a}\right)} - 1\right] - \frac{V+IR_s}{R_{sh}}$$

Equivalent circuit parameters for standard conditions

🟦 🟩 ⬛ 🟪 For each kind of module



Block Parameters: PV Array

PV array (mask) (link)

Implements a PV array built of strings of PV modules connected in parallel. Each string consists of modules connected in series.
Allows modeling of a variety of preset PV modules available from NREL System Advisor Model (Jan. 2014) as well as user-defined PV module.

Input 1 = Sun irradiance, in W/m2, and input 2 = Cell temperature, in deg.C.

Parameters | Advanced

Array data

Parallel strings: 40

Series-connected modules per string: 10

Display I-V and P-V characteristics of ...: array @ 1000 W/m2 & specified temperatures

T_cell (deg. C): [45 25]

Plot

Module data

Module: User-defined

Maximum Power (W): 213.15

Cells per module (Ncell): 60

Open circuit voltage Voc (V): 36.3

Short-circuit current Isc (A): 7.84

Voltage at maximum power point Vmp (V): 29

Current at maximum power point Imp (A): 7.35

Temperature coefficient of Voc (%/deg.C): -0.36099

Temperature coefficient of Isc (%/deg.C): 0.102

Model parameters

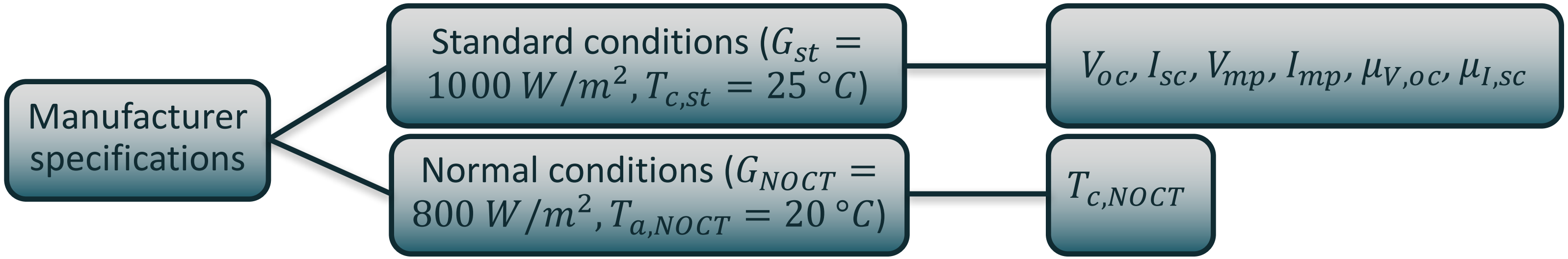
Light-generated current IL (A): 7.8649

Diode saturation current I0 (A): 2.9259e-10

Diode ideality factor: 0.98117

Shunt resistance Rsh (ohms): 313.3991

Series resistance Rs (ohms): 0.39383



Manufacturer specifications

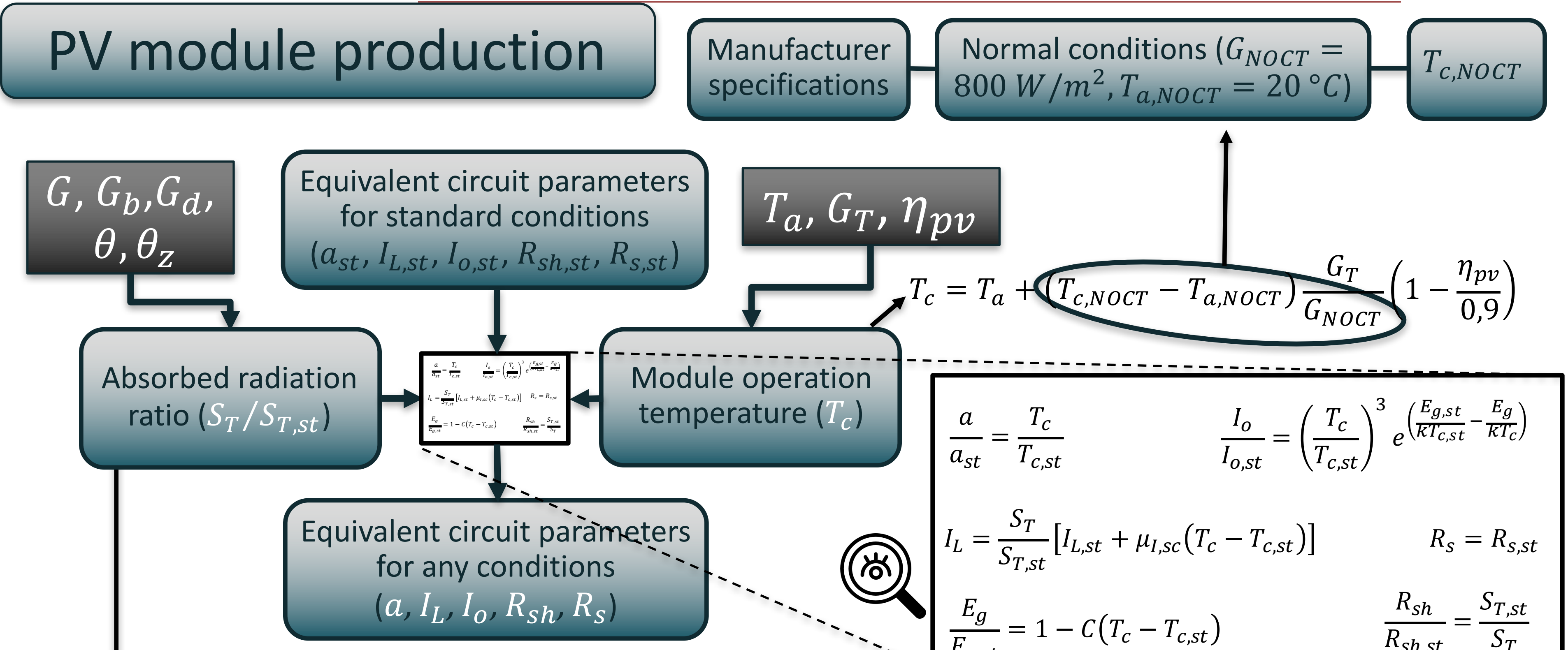
Standard conditions ($G_{st} = 1000\ W/m^2, T_{c,st} = 25\ °C$)

$V_{oc}, I_{sc}, V_{mp}, I_{mp}, \mu_{V,oc}, \mu_{I,sc}$

Normal conditions ($G_{NOCT} = 800\ W/m^2, T_{a,NOCT} = 20\ °C$)

$T_{c,NOCT}$

PV Modelling



PV module production

Manufacturer specifications

Normal conditions ($G_{NOCT} = 800\ W/m^2, T_{a,NOCT} = 20\ °C$)

$T_{c,NOCT}$

$G, G_b, G_d, \theta, \theta_z$

Equivalent circuit parameters for standard conditions ($a_{st}, I_{L,st}, I_{o,st}, R_{sh,st}, R_{s,st}$)

T_a, G_T, η_{pv}

$$T_c = T_a + \left(T_{c,NOCT} - T_{a,NOCT}\right)\frac{G_T}{G_{NOCT}}\left(1 - \frac{\eta_{pv}}{0{,}9}\right)$$

Absorbed radiation ratio ($S_T/S_{T,st}$)

Module operation temperature (T_c)

Equivalent circuit parameters for any conditions (a, I_L, I_o, R_{sh}, R_s)

$$\frac{a}{a_{st}} = \frac{T_c}{T_{c,st}} \qquad \frac{I_o}{I_{o,st}} = \left(\frac{T_c}{T_{c,st}}\right)^3 e^{\left(\frac{E_{g,st}}{kT_{c,st}} - \frac{E_g}{kT_c}\right)}$$

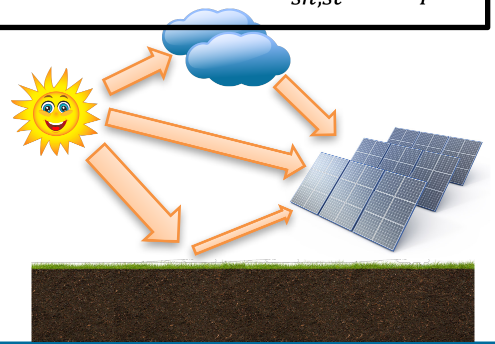
$$I_L = \frac{S_T}{S_{T,st}}\left[I_{L,st} + \mu_{I,sc}\left(T_c - T_{c,st}\right)\right] \qquad R_s = R_{s,st}$$

$$\frac{E_g}{E_{g,st}} = 1 - C\left(T_c - T_{c,st}\right) \qquad \frac{R_{sh}}{R_{sh,st}} = \frac{S_{T,st}}{S_T}$$

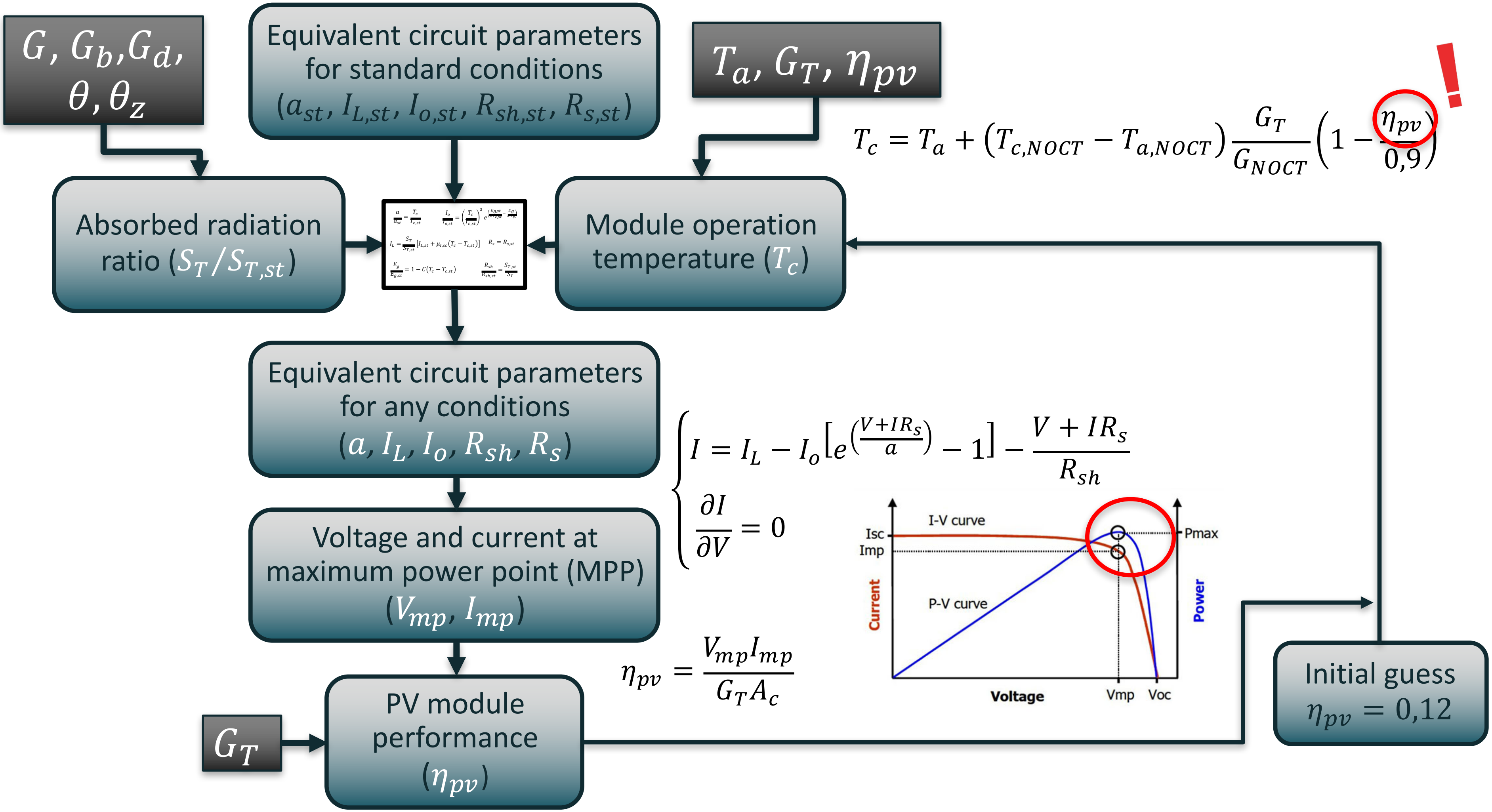
$$\frac{S_T}{S_{T,st}} = M_a\left(\overbrace{\frac{G_b}{G_{st}}R_bK_{\tau\alpha,b}}^{\text{Beam}} + \overbrace{\frac{G_d}{G_{st}}K_{\tau\alpha,d}\frac{1+\cos\beta}{2}}^{\text{Isotropic diffuse}} + \overbrace{\frac{G_b+G_d}{G_{st}}\rho_gK_{\tau\alpha,g}\frac{1-\cos\beta}{2}}^{\text{Ground-reflected}}\right)$$

Air mass modifier
“atmosphere effect”

Incidence angle modifiers
“glass cover effect”



PV Modelling



$G, G_b, G_d, \theta, \theta_z$

Equivalent circuit parameters for standard conditions $(a_{st}, I_{L,st}, I_{o,st}, R_{sh,st}, R_{s,st})$

T_a, G_T, η_{pv}

$$T_c = T_a + (T_{c,NOCT} - T_{a,NOCT})\frac{G_T}{G_{NOCT}}\left(1 - \frac{\eta_{pv}}{0{,}9}\right)$$

Absorbed radiation ratio $(S_T/S_{T,st})$

$$\frac{a}{a_{st}} = \frac{T_c}{T_{c,st}} \qquad \frac{I_o}{I_{o,st}} = \left(\frac{T_c}{T_{c,st}}\right)^3 e^{\left(\frac{E_{g,st}}{kT_{c,st}} - \frac{E_g}{kT_c}\right)}$$

$$I_L = \frac{S_T}{S_{T,st}}\left[I_{L,st} + \mu_{I,sc}(T_c - T_{c,st})\right] \qquad R_s = R_{s,st}$$

$$\frac{E_g}{E_{g,st}} = 1 - C(T_c - T_{c,st}) \qquad \frac{R_{sh}}{R_{sh,st}} = \frac{S_{T,st}}{S_T}$$

Module operation temperature (T_c)

Equivalent circuit parameters for any conditions $(a, I_L, I_o, R_{sh}, R_s)$

$$\begin{cases} I = I_L - I_o\left[e^{\left(\frac{V+IR_s}{a}\right)} - 1\right] - \dfrac{V + IR_s}{R_{sh}} \\ \dfrac{\partial I}{\partial V} = 0 \end{cases}$$

Voltage and current at maximum power point (MPP) (V_{mp}, I_{mp})

$$\eta_{pv} = \frac{V_{mp}I_{mp}}{G_T A_c}$$

G_T

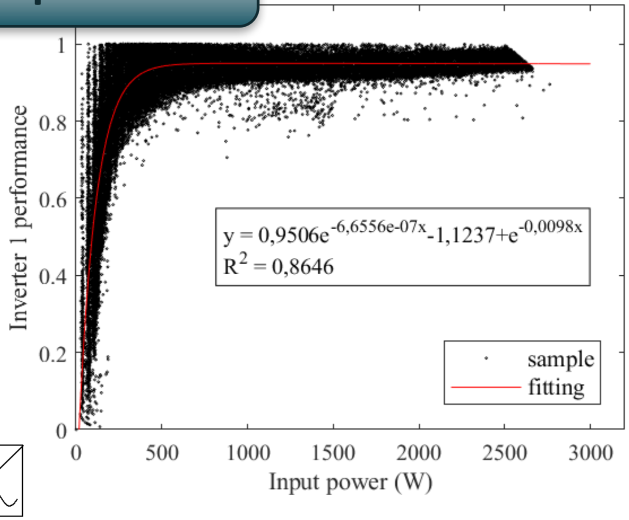
PV module performance (η_{pv})

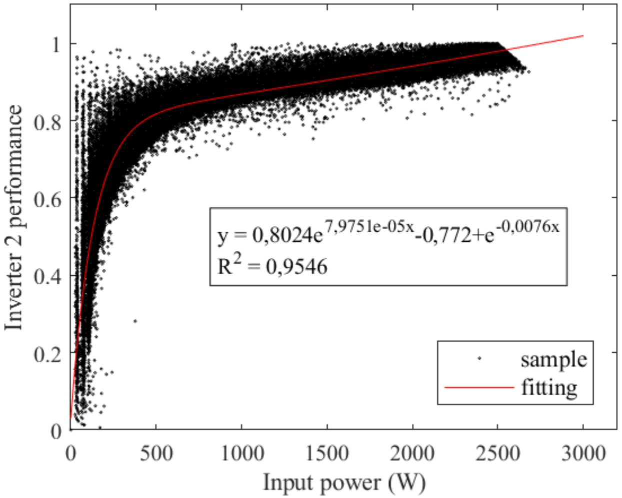
Initial guess $\eta_{pv} = 0{,}12$

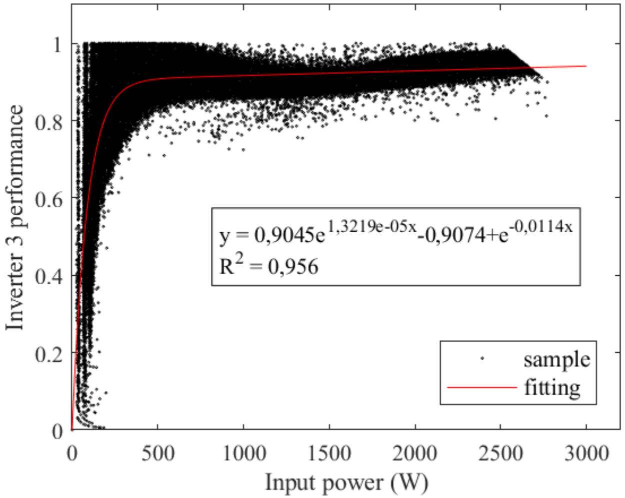
PV Modelling

Power-conditioning equipment

CIESOL PV field







- Fitting for $\eta_{inv} - P_{dc}$

- R^2 values close to 1

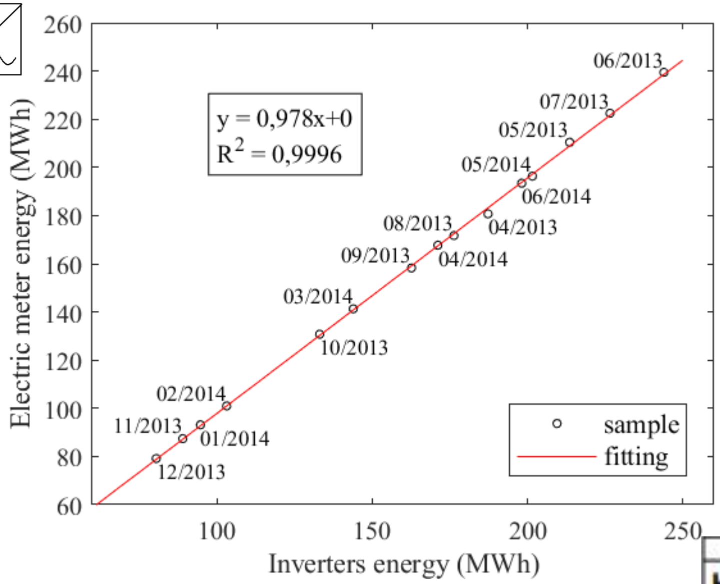
- Results vary between inverters

- Dependency with other variables?

PV Modelling

Power-conditioning equipment

Parking PV field



Power (P_{ac})	Fronius Agilo 100 460 V / 820 V	Fronius IG+ 55v3 230 V / 370 V / 500 V
5 % of $P_{ac,r}$	90.5 / 84.8 %	90.5 / 91.6 / 89.9 %
10 % of $P_{ac,r}$	94.6 / 91.5 %	91.5 / 92.2 / 90.8 %
20 % of $P_{ac,r}$	96.6 / 94.7 %	93.4 / 93.6 / 93.3 %
25 % of $P_{ac,r}$	96.9 / 95.4 %	94.1 / 94.2 / 93.3 %
30 % of $P_{ac,r}$	97.0 / 95.7 %	94.4 / 94.5 / 93.8 %
50 % of $P_{ac,r}$	97.2 / 96.3 %	94.7 / 95.4 / 94.7 %
75 % of $P_{ac,r}$	96.9 / 96.1 %	95.2 / 95.7 / 95.0 %
100 % of $P_{ac,r}$	96.5 / 95.7 %	95.3 / 95.9 / 95.2 %

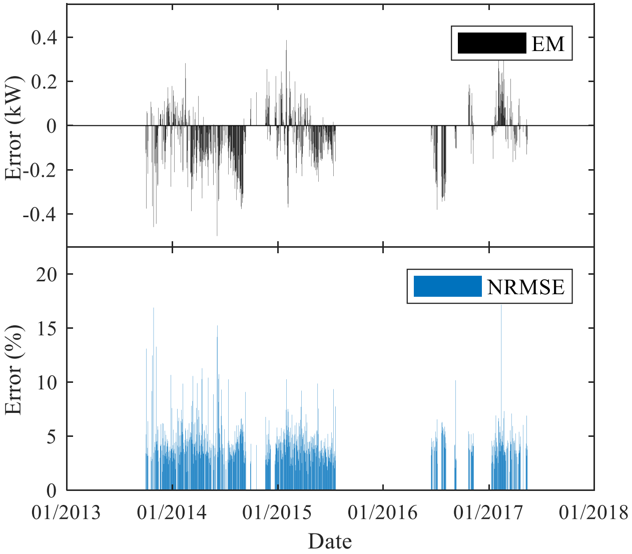
Power	Fronius Agilo 100	Fronius IG+ 55v3
DC ($P_{dc,r}$)	104,4 kW	5,25 kW
AC ($P_{ac,r}$)	100 kW	5 kW

- Linear interpolations to get η_{inv} for inverters

- Constant coefficient η_{ac} for losses between these and the electric meter

PV Modelling

CIESOL PV field



Indicator	Max.	Min.	Mean
EM [W]	387	-499	-57
NRMSE [%]	17,2	1,5	4,5

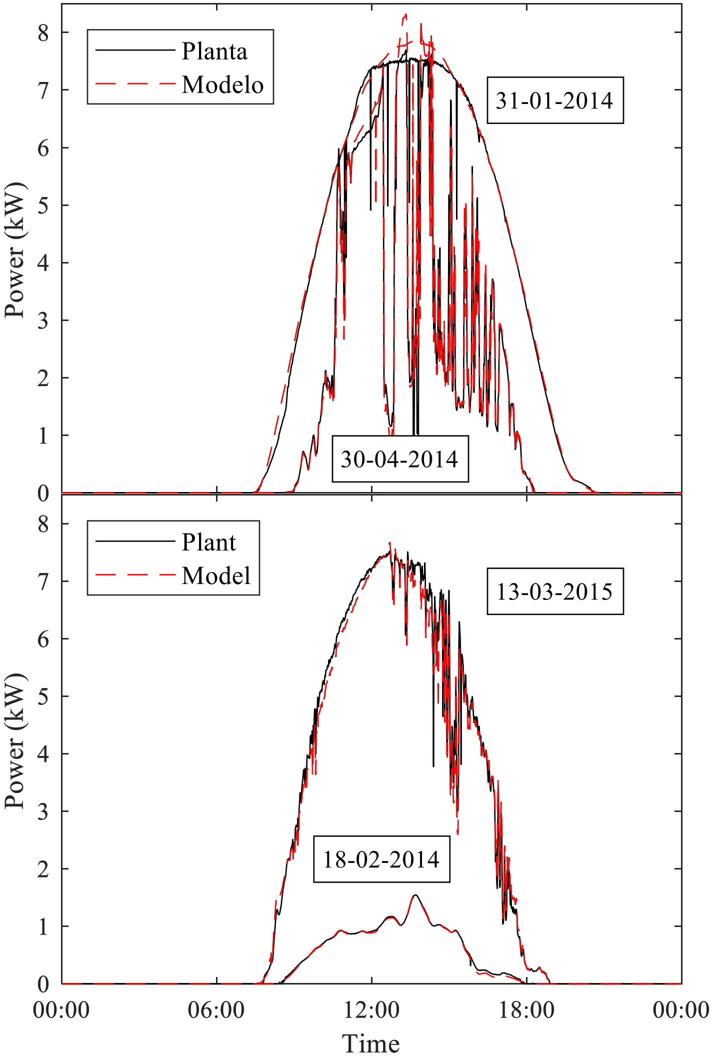
Quantitative validation:

- Daily mean error (black) and root mean square error (blue)

- Gaps correspond to missing data

Qualitative validation:

- Days with high NRMSE (up) and low NRMSE (down) with different weather conditions



PV Modelling

Parking PV field

Quantitative validation:

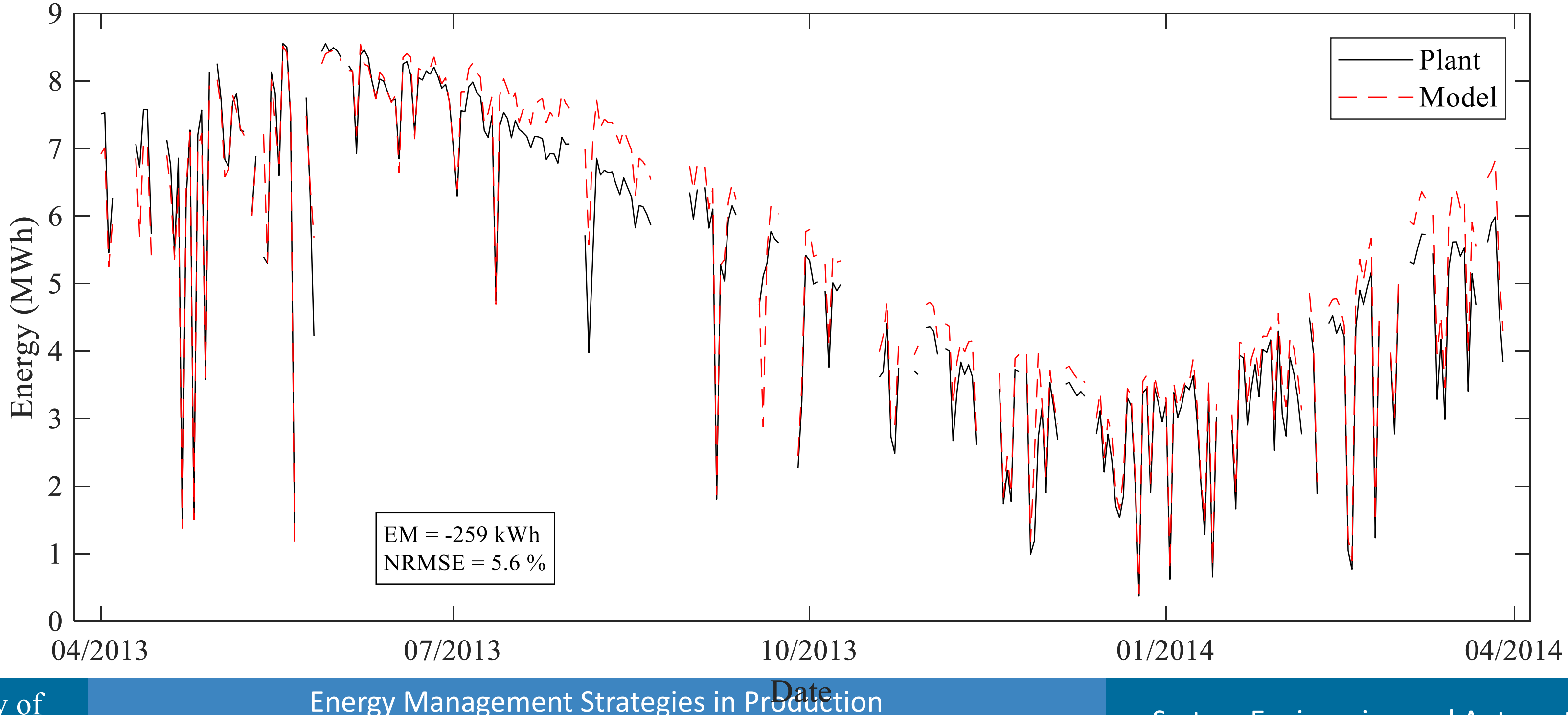
- Same indicators but for the entire period

- Production underestimated

Qualitative validation:

- Production fluctuates with radiation during the year

- Peaks correspond to cloudiness



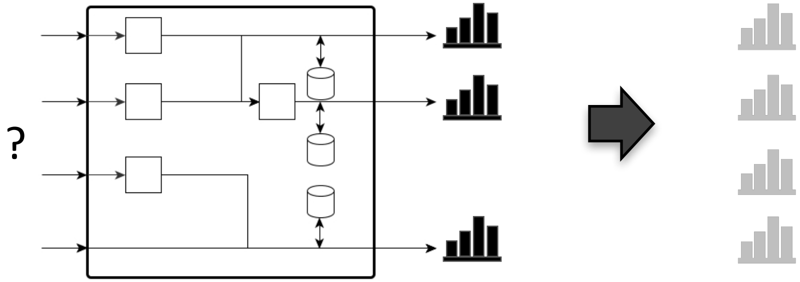
Optimization results

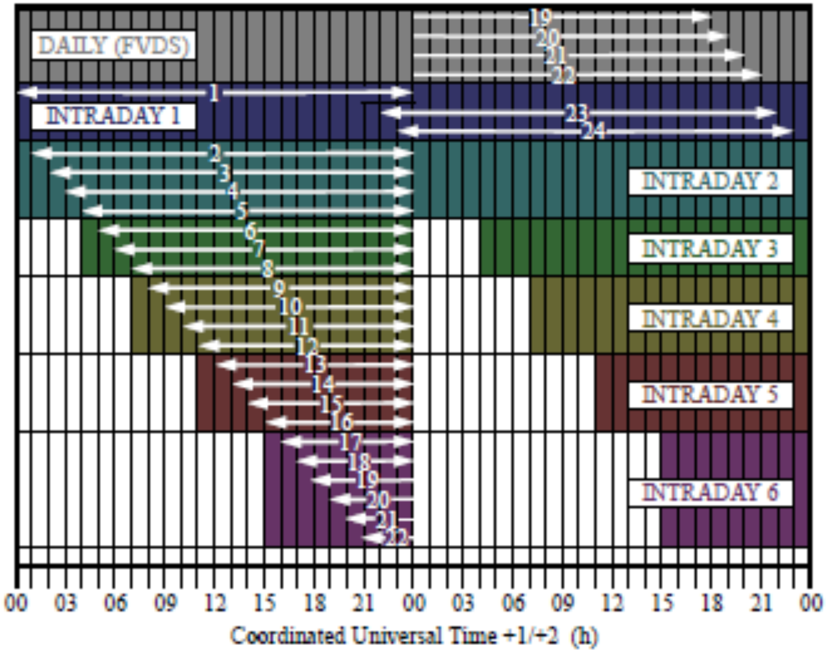
Control strategy

MPC based on economic criteria: deterministic approach based on real data

$$\min \sum_{k=1}^{H\frac{60}{T}} (\boldsymbol{c}(k)\boldsymbol{I}(k) - \boldsymbol{s}(k))\boldsymbol{M}(k)\frac{T}{60}$$

$$\text{s.t.} \quad \text{the aforementioned constraints}$$





- From 0 h to 18 h (UTC+1/UTC+2) H is shorted in order to make it equal to the difference between the current time and midnight, the period when the electricity price is known.

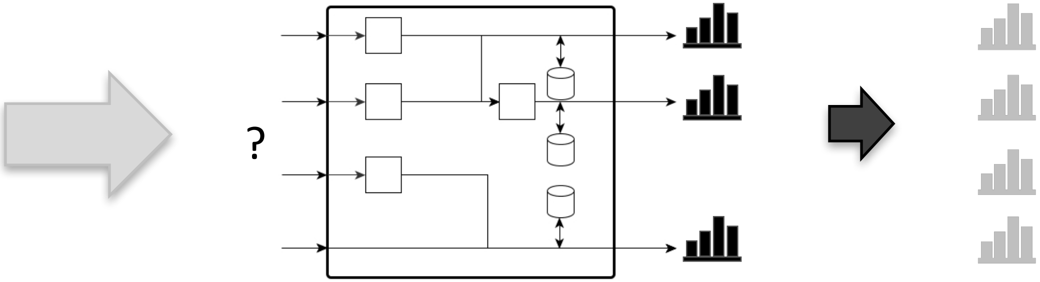
- From 18 h to 24 h (UTC+1/UTC+2) electricity price is published for the whole following day, so H takes a value of 24 h.

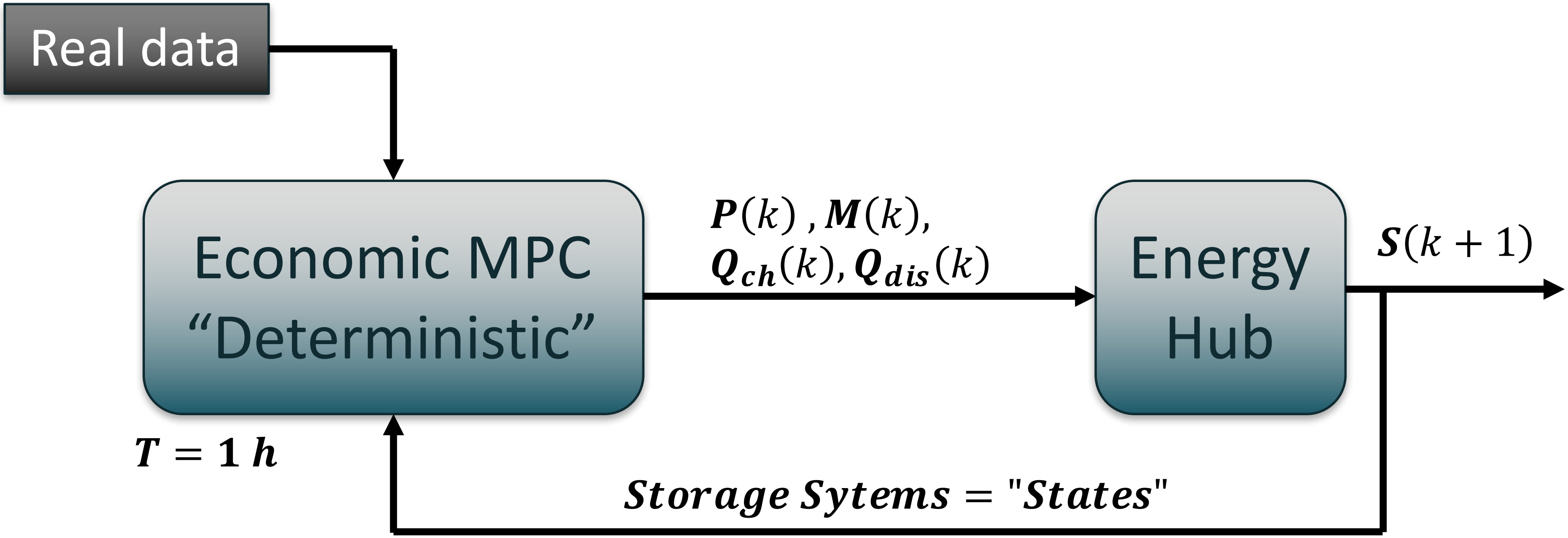
Control strategy

MPC based on economic criteria: deterministic approach based on real data

$$\min \sum_{k=1}^{H\frac{60}{T}} (\boldsymbol{c}(k)\boldsymbol{I}(k) - \boldsymbol{s}(k))\boldsymbol{M}(k)\frac{T}{60}$$

s.t. the aforementioned constraints





Real data

Economic MPC "Deterministic"

$\boldsymbol{P}(k)$, $\boldsymbol{M}(k)$, $\boldsymbol{Q}_{\boldsymbol{ch}}(k)$, $\boldsymbol{Q}_{\boldsymbol{dis}}(k)$

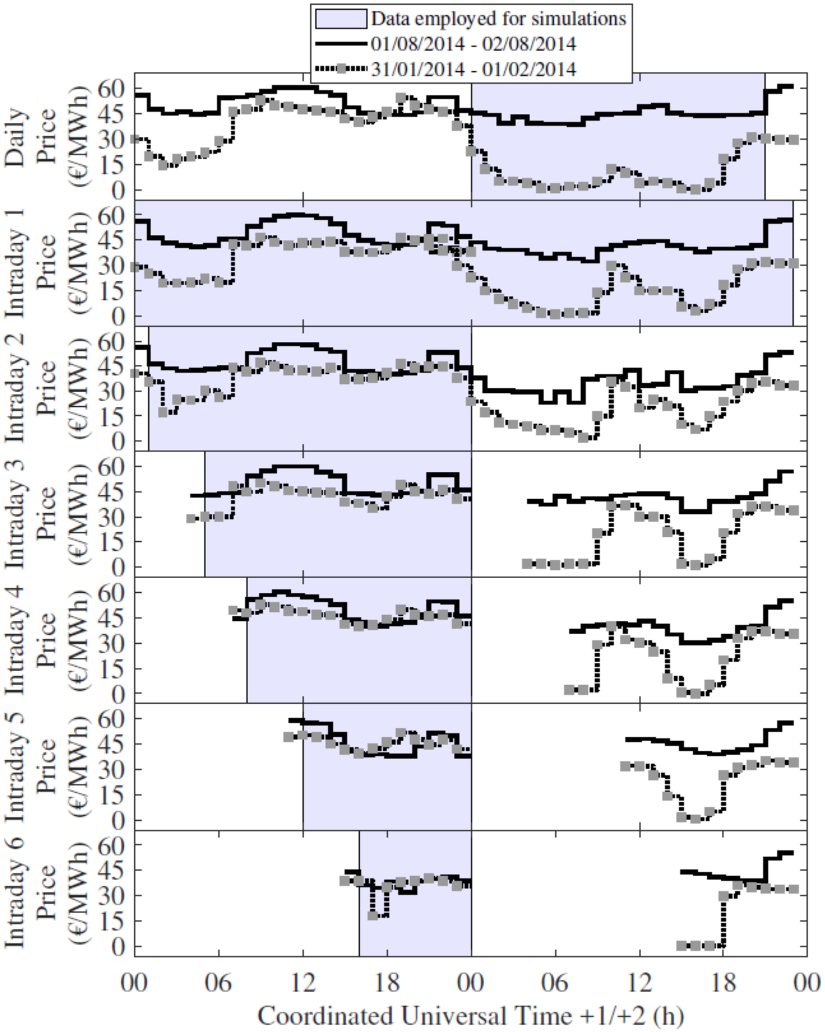
Energy Hub

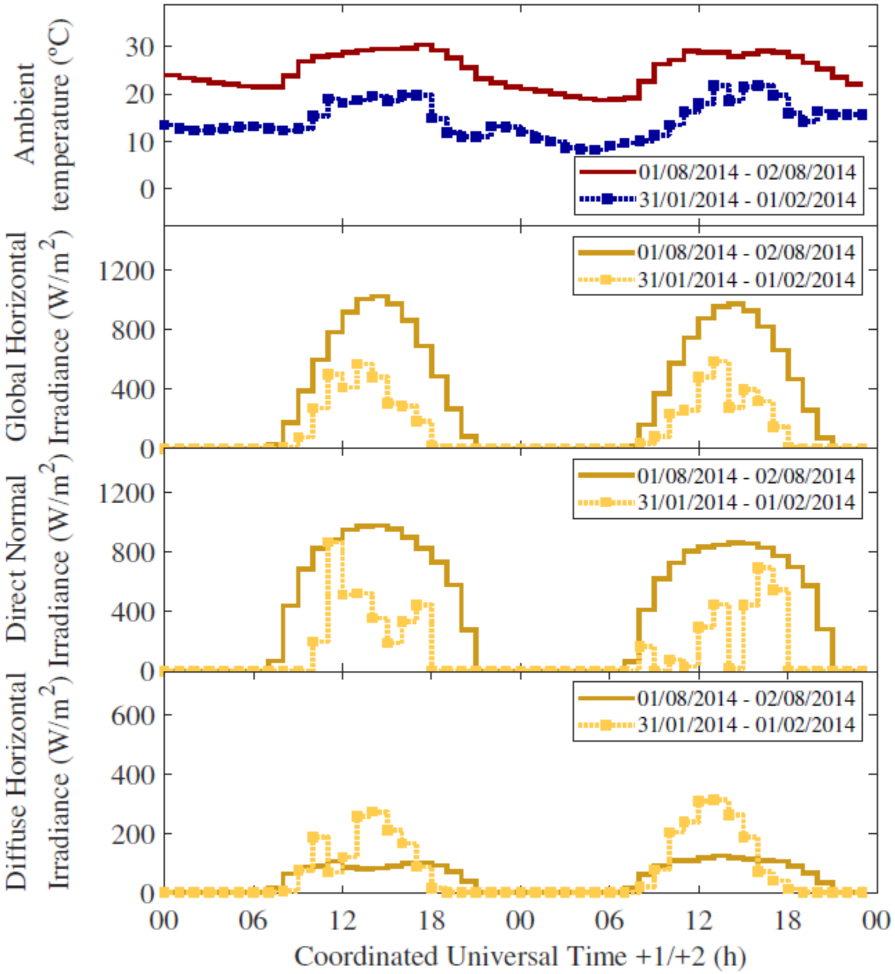
$\boldsymbol{S}(k+1)$

$\boldsymbol{T = 1\ h}$

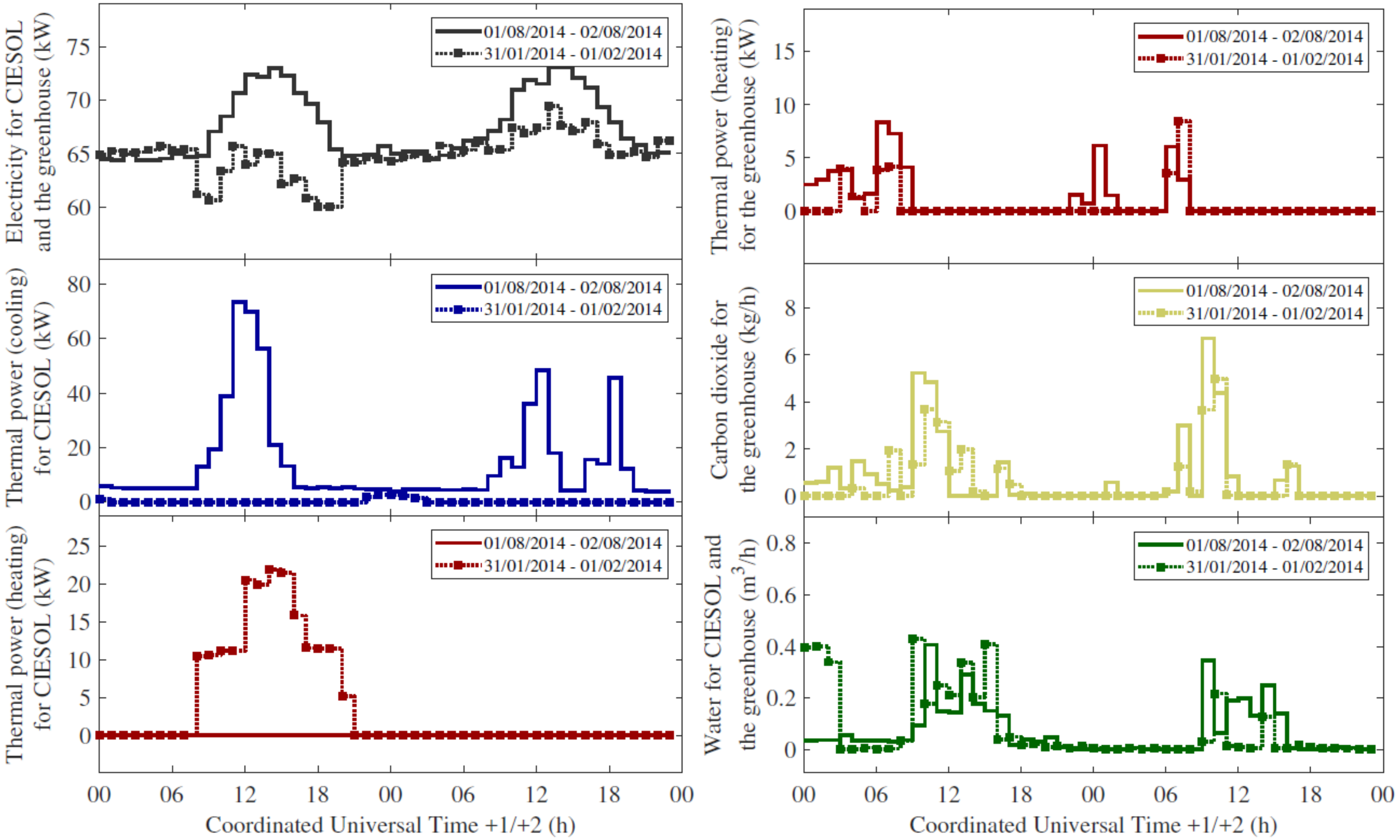
$\boldsymbol{Storage\ Sytems = "States"}$

Simulation scenarios

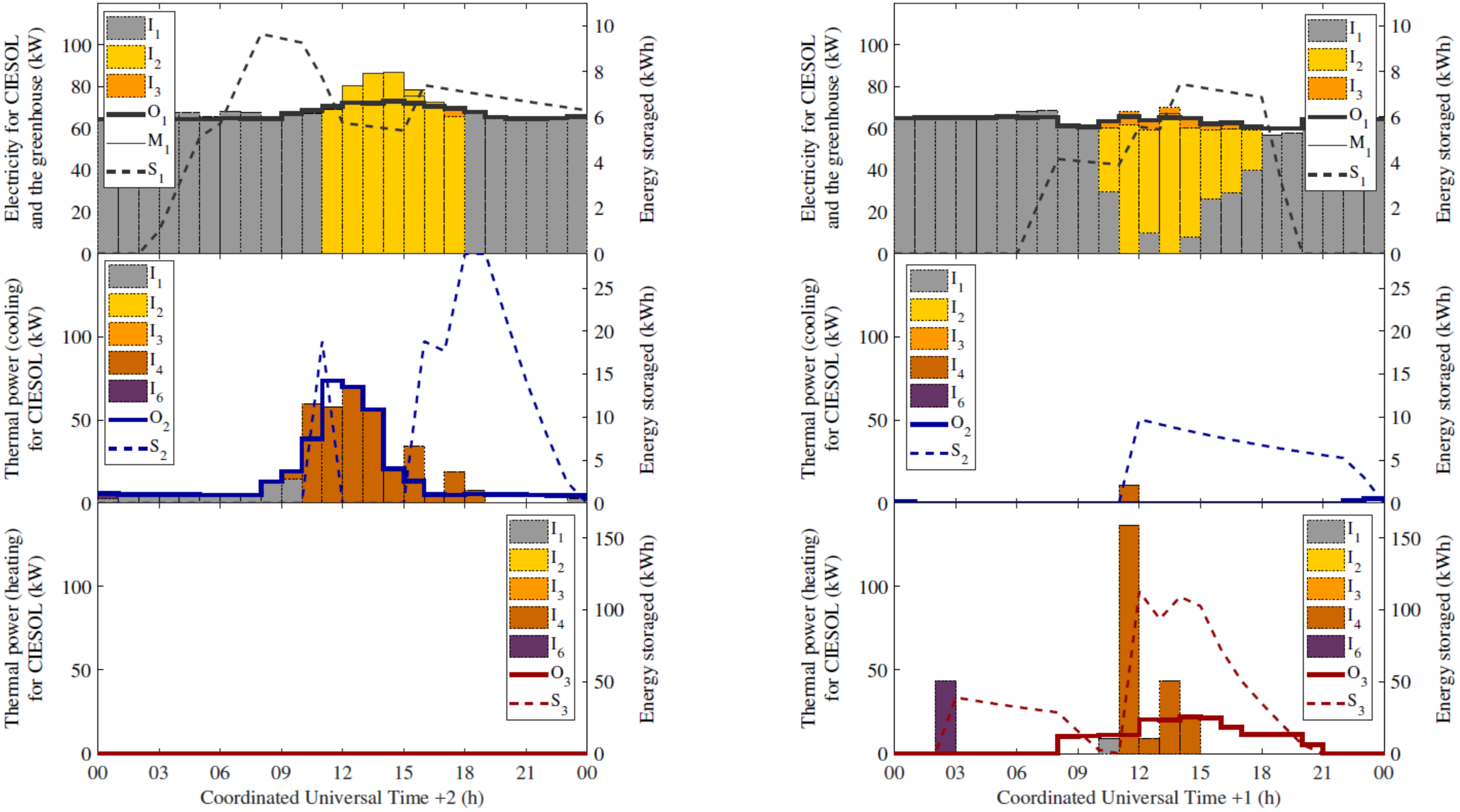




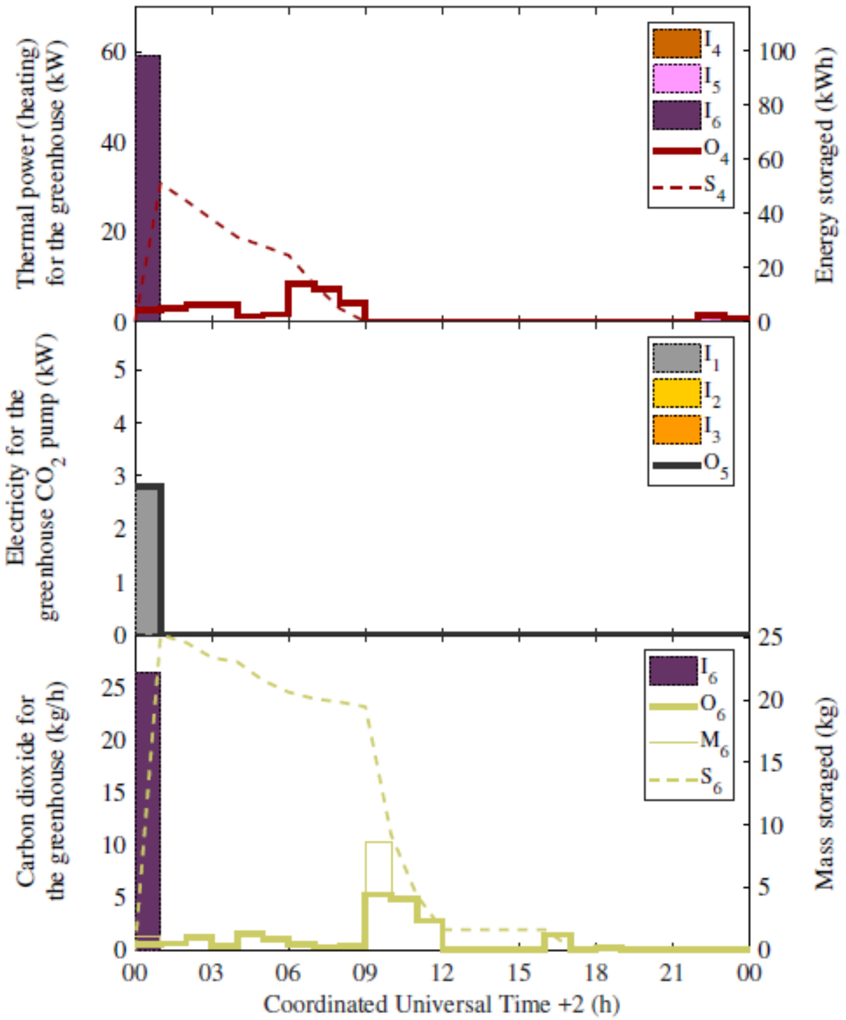
Simulation scenarios

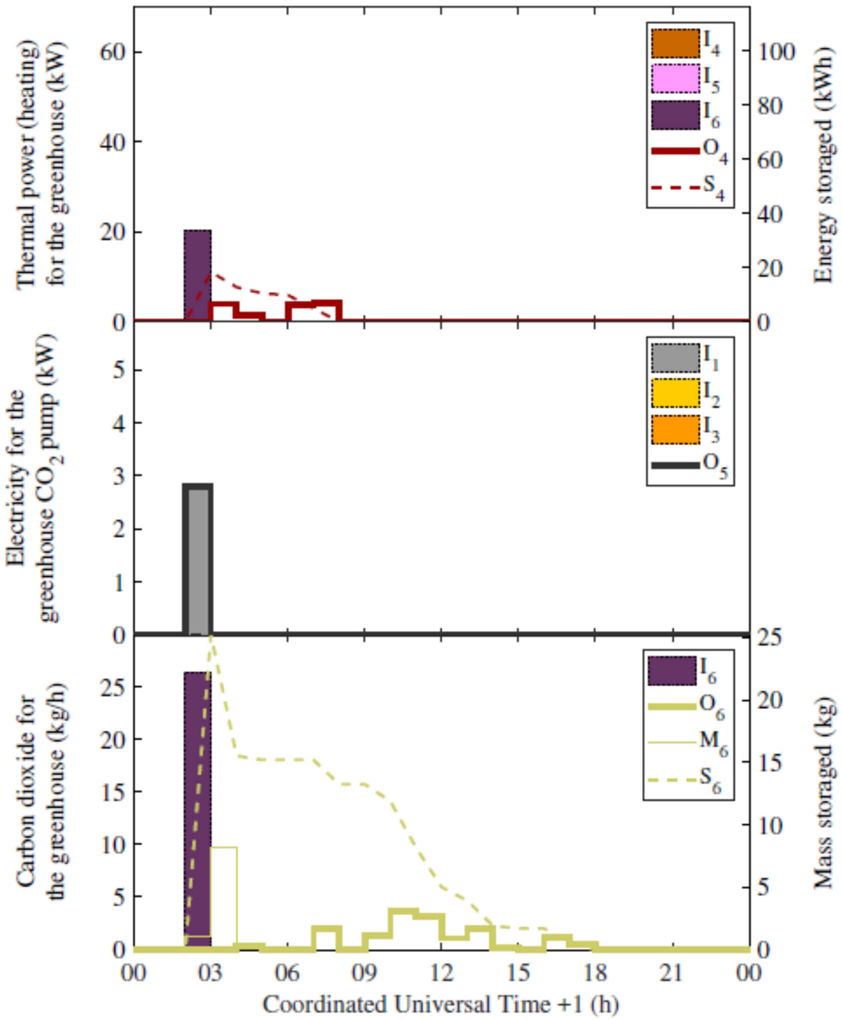


Simulation results

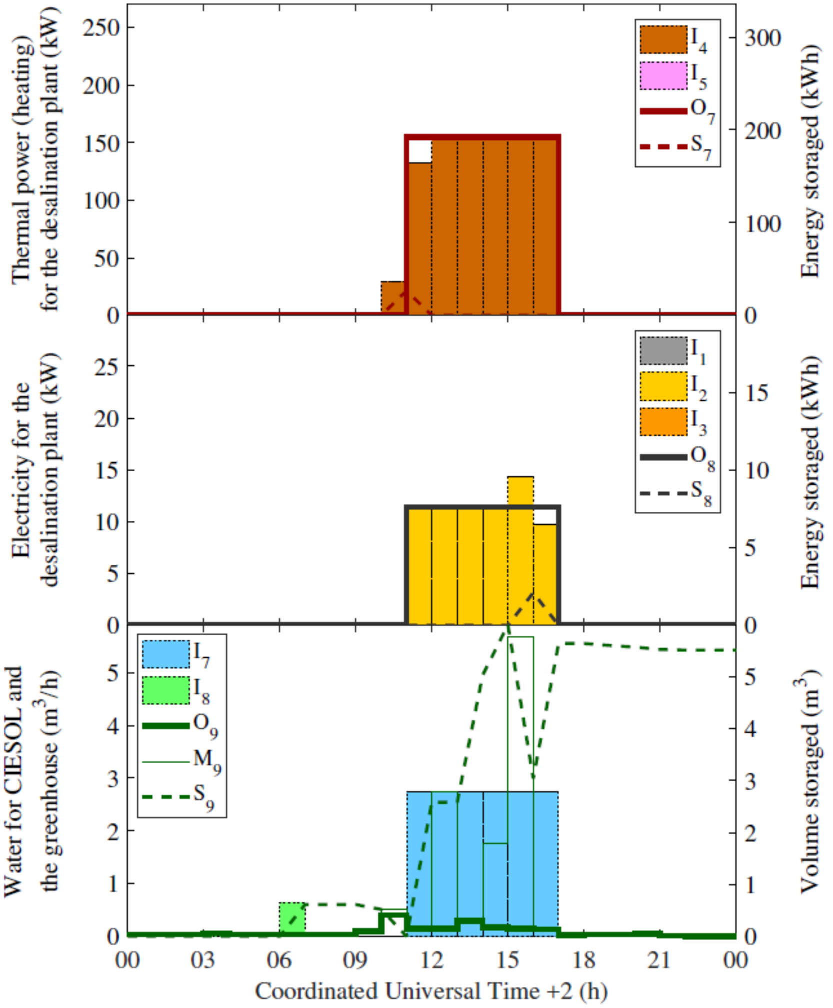


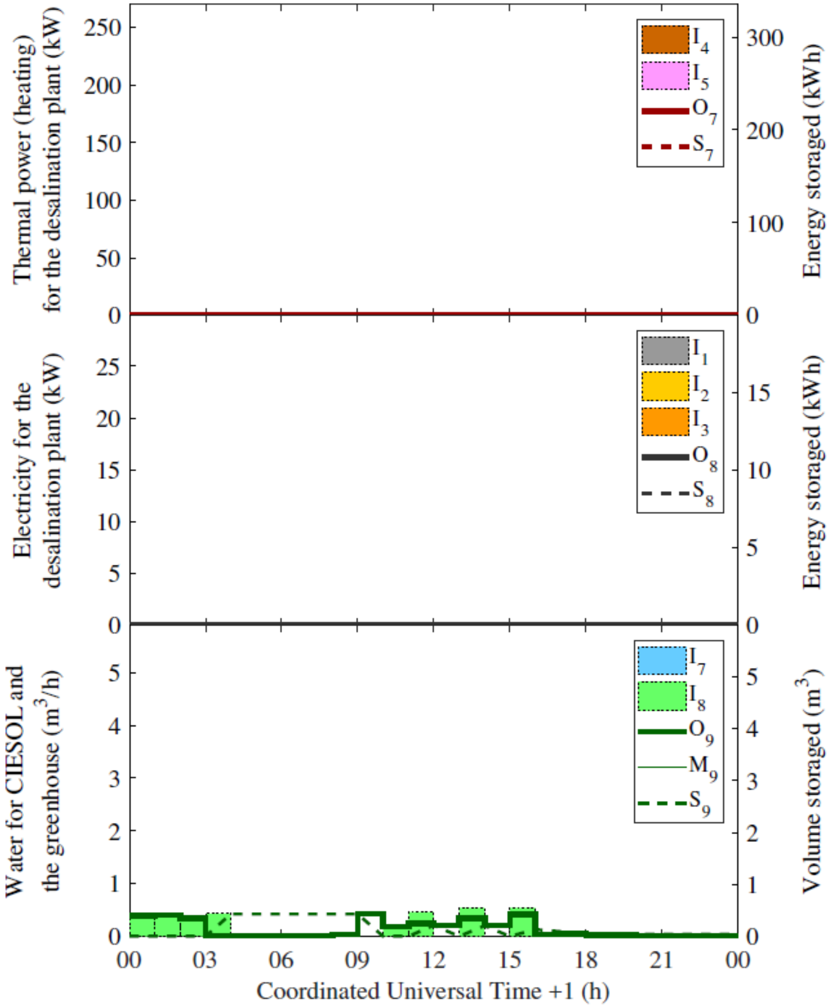
Simulation results





Simulation results





Extending the model and further applications

Maximum activations constraint

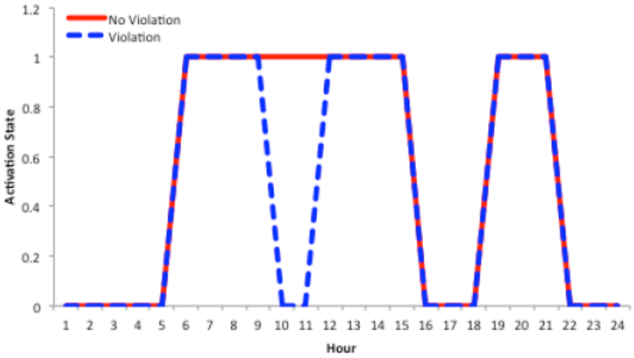
Problem: Frequent start ups and shut downs of certain technologies can be damaging, so you sometimes need to limit the number of start ups and shut downs that are allowed in a given time period.

Solution: Add 2 binary variables:

- $\delta_{on/off}$ = status change in technology operation
- $\delta_{i,t,CHP}$ = current status of technology operation

$$\delta_{on/off} = \left|\left(\delta^{on}_{i,t,CHP} - \delta^{on}_{i,t-1,CHP}\right)\right| \ \forall i$$

↑ Now ↑ Previous timestep



0 if state remains the same

1 if state changes

(-1 if shutdown)

(+1 if start-up)

Minimum run time constraint

Problem: Some equipment must run continuously for a minimum amount of time, due to the nature of the process, mechanical concerns or need to maintain a reasonable efficiency.

- e.g.: CHP plants and heat pumps have poor efficiency for some time after starting.

Solution:

- Formulate the model such that a given device must operate for a minimum run time of t_m timesteps.
- Calculate a variable *z(t)* that tells you the nature of change in the device's operation between timesteps.

$$z(t) = a*\overset{\substack{\text{Operation}\\ \text{previous timestep}\\ \downarrow}}{P(t-1)} - b*\overset{\substack{\text{Operation}\\ \text{this timestep}\\ \downarrow}}{P(t)}$$

if a=0.5 and b=1:

$$\begin{aligned}
P(t-1) &= 0, P(t) = 0 \Rightarrow z(t) = 0 \\
P(t-1) &= 0, P(t) = 1 \Rightarrow z(t) = -b = -1 \\
P(t-1) &= 1, P(t) = 1 \Rightarrow z(t) = a - b = -0.5 \\
P(t-1) &= 1, P(t) = 0 \Rightarrow z(t) = a = 0.5
\end{aligned}$$

z(t) = 0; still off
z(t) = -1; start-up
z(t) = -0.5; still on
z(t) = 0.5; shutdown

Ramping constraint

Problem: Some conversion technologies are limited in how quickly they can ramp up or down their energy output.

Solution: Add a set of constraints that control the difference in energy production levels between two consecutive time intervals.

$$\underset{\downarrow}{\text{Power output this timestep}} \qquad \underset{\downarrow}{\text{Power output previous timestep}}$$

$$P_m(t) - P_m(t-1) \leq R^{up} \longleftarrow \text{Maximum allowable amount of ramping up}$$

$$P_m(t-1) - P_m(t) \leq R^{down} \longleftarrow \text{Maximum allowable amount of ramping down}$$

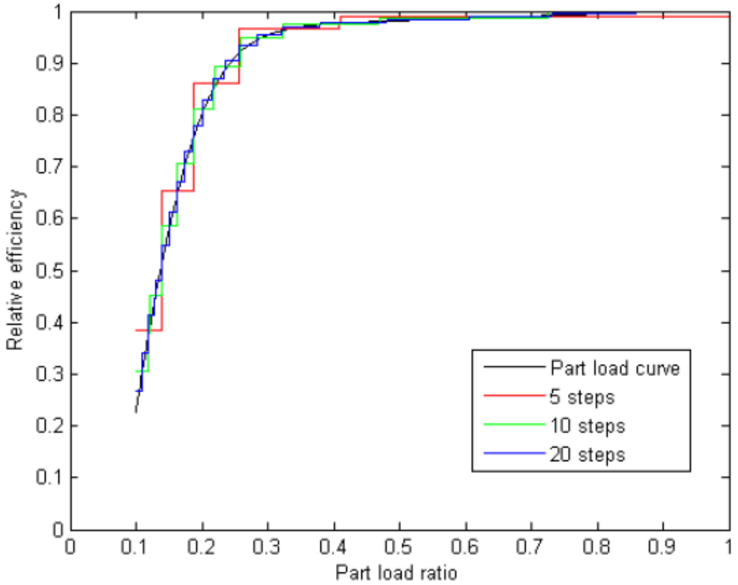
Stepwise linearization of conversion efficiencies

Problem: Many technologies have efficiencies that depend nonlinearly on the power output.

Solution: Linearization of the efficiency curve:

1. Define the number/ranges of segments/steps into which to divide the original curve.
2. Define a virtual "bin" for each load segment, and add a binary variable for each bin.
3. Add a "knapsack" constraint, so that only one bin can be active.
4. Add power output constraints for each bin; set the efficiency according to the bin.

Possibilities for stepwise linearization of conversion efficiency



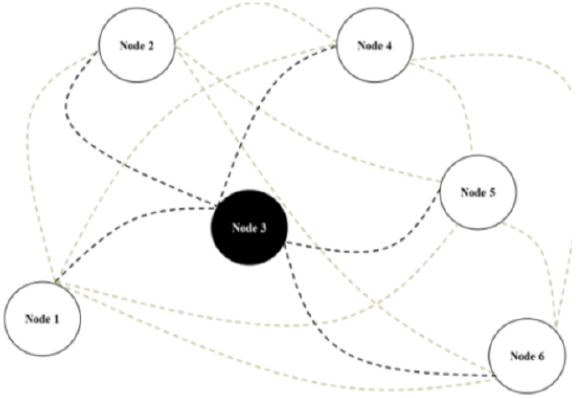
Representing and designing networks

Energy flowing out of the node (from node i to j)

Energy flowing into the node (from node j to i)

Modified load balance constraint:

$$L_k(t) = \underbrace{\Theta_{k,m} \times P_m(t)}_{\text{conversion}} + \underbrace{A_n^{dis} Q_n^{dis}(t) - Q_n^{ch}(t)}_{\text{storage}} \quad \underbrace{+ R_{i,j}{}^{out}(t) \quad - R_{j,i}{}^{in}(t)}_{\text{network}}$$



Equation to account for network losses: $R_{i,j}{}^{out}(t) = A_R R_{i,j}{}^{in}\ (t)$

A_R = network loss

Variable: Binary variable for each possible link indicating the installation of that link

$$\delta_{i,j}^{pipe}$$

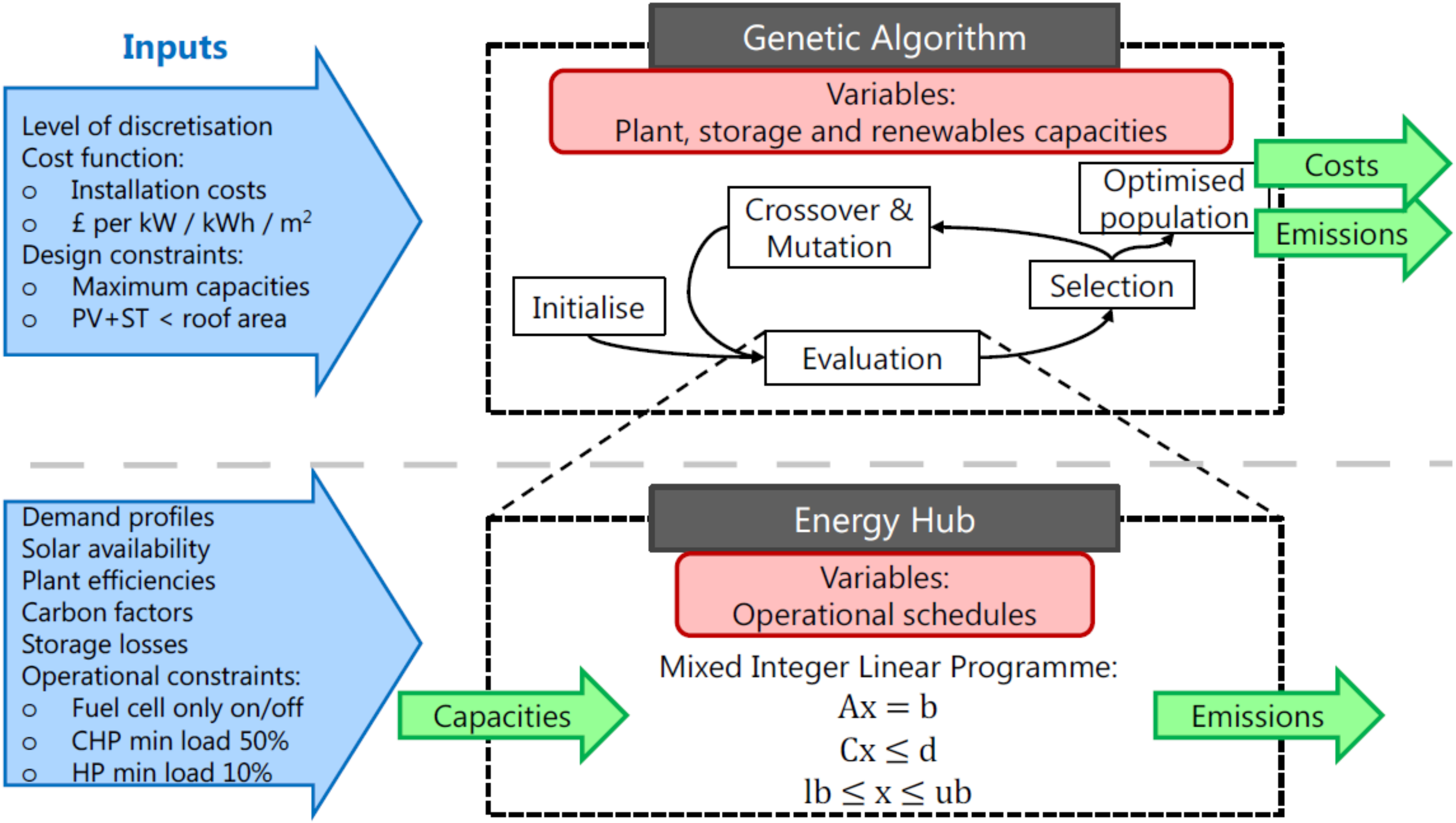
Constraint: Energy can only flow in one direction through a link

$$\delta_{i,j}^{pipe} + \delta_{j,i}^{pipe} \leq 1 \qquad \forall i,j \; where \; j > i$$

Constraint: If a link is installed, then energy can be transferred via that link

$$H_{i,j,t}^{pipe-out} \leq M \cdot \delta_{i,j}^{pipe} \qquad \forall i,j \; where \; j \neq i$$

Layout design and sizing



Inputs

Level of discretisation
Cost function:
- Installation costs
- £ per kW / kWh / m^2

Design constraints:
- Maximum capacities
- PV+ST < roof area

Demand profiles
Solar availability
Plant efficiencies
Carbon factors
Storage losses
Operational constraints:
- Fuel cell only on/off
- CHP min load 50%
- HP min load 10%

Mixed Integer Linear Programme:

$$Ax = b$$
$$Cx \leq d$$
$$lb \leq x \leq ub$$

Others

- Multi-objective optimization
- Stochastic and robust optimization for uncertainty
- Improving computational efficiency formulations


That's all Folks!