PhD study: general information

- PhD student: Tokhir Gafurov
- Thesis title: "Reliability of power systems with high penetration of renewables"
- Directors:
  - ✓ Julio Usaola (UC3M)
  - ✓ Milan Prodanovic (IMDEA Energía)
- Period: 06.2012 – 12.2014 (approx.)
- Funding: IMDEA Energía
- Planned research stay at KTH, Sweden

PhD study: objectives and methods

- Adequacy analysis for power systems at high penetration of renewables (HL1)
  - ✓ Development of renewable energy models (solar, wind, hydro)
  - ✓ Creation of Sequential Monte-Carlo simulation tool integrated with renewable energy models
  - ✓ Main investigation on power system reliability and the involved modeling aspects (to be decided)

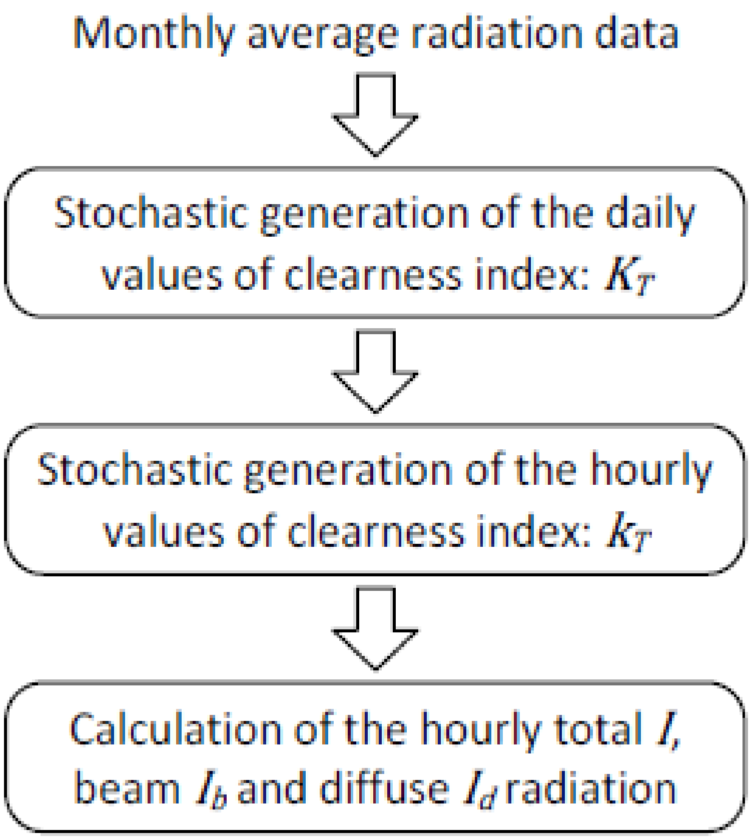
PhD study: work plan

Year and trimester	**2012**		**2013**				**2014**			
	3	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
1. Solar generation: solar irradiation	x									
2. Solar generation: solar power plants		x	x							
3. Power system reliability assessment program (Sequential Monte Carlo)				x						
4. Wind generation										
5. Hydro power generation and storage										
6. Simulations / main investigation (climatological adequacy, scenario reduction, reliability assessment)										
7. Writing thesis			x							

PhD study: completed parts

- Solar resource model for creating hourly synthetic sequence of solar radiation values
- Models of solar power plants: PV and CSP (trough and tower)

Solar resource model: description



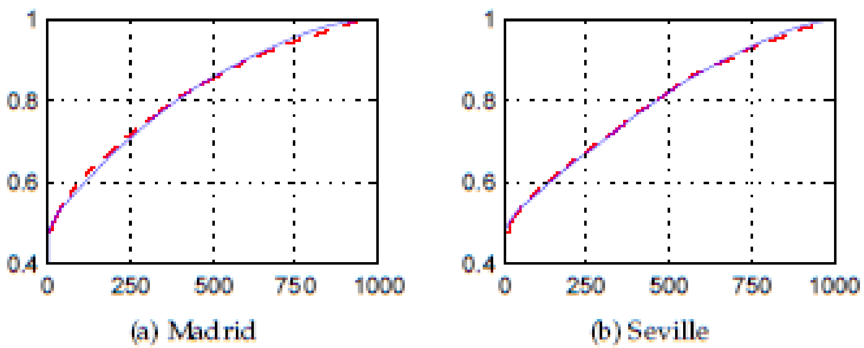
[1] R.J. Aguiar, M. Collares-Pereira, and J.P. Conde. Simple procedure for generating sequences of daily radiation values using a library of Markov transition matrices. Solar Energy, 40(3):269–279, 1988.

[2] R.J. Aguiar and M. Collares-Pereira. TAG: A time-dependent, autoregressive, Gaussian model for generating synthetic hourly radiation. Solar Energy, 49(3):167–174, 1992.

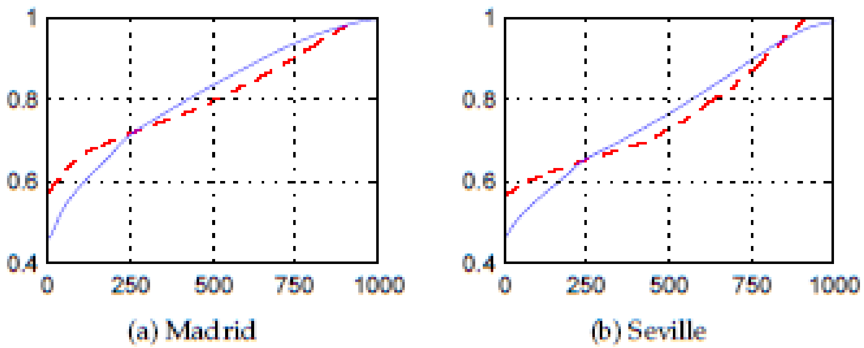
[3] B. Ridley, J. Boland, and P. Lauret. Modeling of diffuse solar fraction with multiple predictors. Renewable Energy, 35(2):478–483, 2010.

Solar resource model: validation

- Comparison with TMY data
- Ideal match for total radiation
- Monthly deviations in beam radiation - 7.1%



CDF for total radiation



CDF for direct normal radiation

PV system model: description

- Calculation of solar radiation on a tilted plane
  - ✓ HDKR model is selected
- Conversion of incident radiation to net power
  - ✓ five-parameter model is applied in reduced form
  - ✓ assumption 1: operation at maximum power point
  - ✓ assumption 2: normalized total incident radiation is equal to the absorbed value, i.e. $G_t/G_{src}=G_{eff}/G_{eff,src}$

PV system model: validation (I)

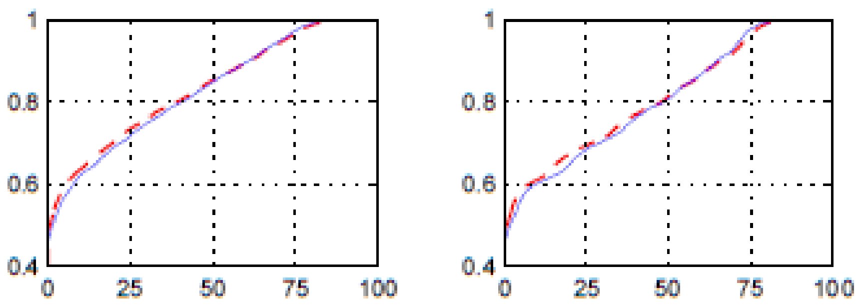
- Comparison with SAM simulations (Sandia model)
- Fictious PV system
  - ✓ capacity 100MW, orientation towards equator, tilt angle equal to latitude, parasitic losses 9.2%
  - ✓ 4 PV cell technologies

Cell type	Siemens SP-75 (c-Si)	Solarex MSX-64 (mc-Si)	AstroPower APX-90 (Si-film)	Uni-Solar US-64 (3-a-Si)
NOCT [°C]	43.7	43.3	43.0	37.9
$\eta_{pv,src}$ [%]	11.29	10.76	8.34	6.32
β_{Voc} [1/°C]	-0.004158	-0.003774	-0.004384	-0.004131
A_{pv} [m2]	887470	932426	1202120	1582520

PV system model: validation (II)

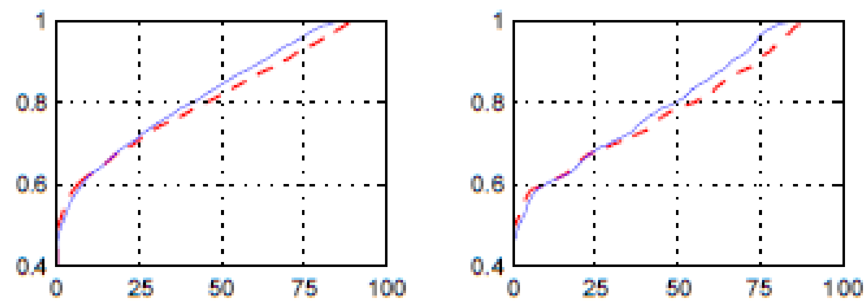
	Siemens	Solarex	AstroPower	Uni-Solar
Minimum	-10.45	-8.61	-3.93	-13.31
Maximum	+4.71	+6.91	+9.52	+8.60
Absolute mean	2.37	3.01	4.24	7.56

Deviations (%) in monthly net production



(a) Madrid (b) Seville

CDFs for net power (AstroPower)



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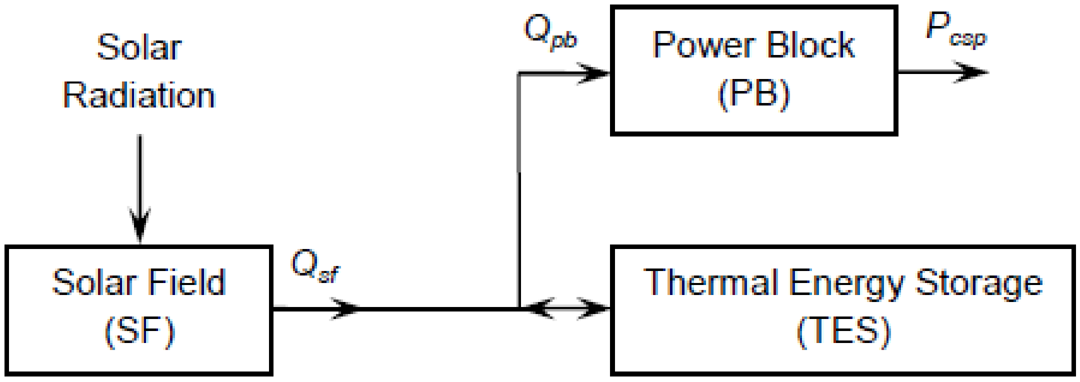
CDFs for net power (Uni-Solar)

CSP plant models: description (I)

- Solar field: $I_{b,n} \rightarrow Q_{sf}$
- Power cycle: $Q_{sf} \rightarrow P_{gross}$
- Parasitic losses: $P_{gross} \rightarrow P_{net}$



CSP plant models: description (II)

- Solar field efficiency:
  - ✓ parabolic trough

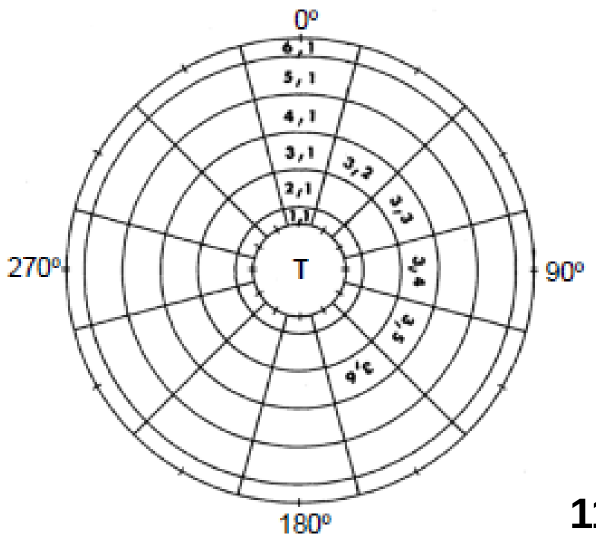
$$\eta_{sf} = \cos\theta \times \eta_{ptr} \times \eta_{shbl} \times \eta_{sf,other}$$

$$\eta_{ptr} = \eta_{ptr,max}\, IAM - C_{ptr}\,(T_{HTF} - T_{amb})/I_{b,n}$$

  - ✓ central receiver

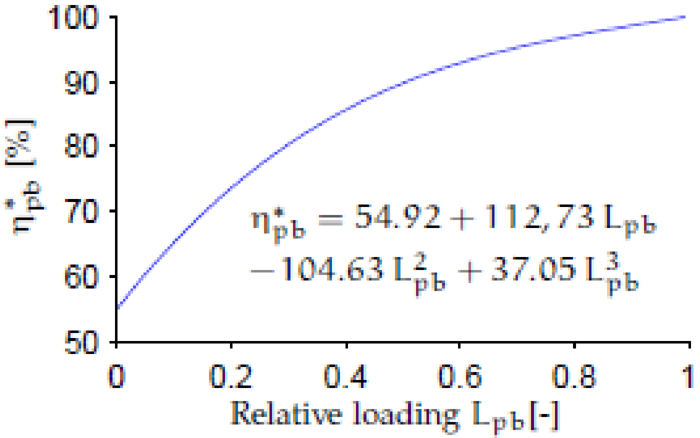
$$\eta_{sf} = \left(\eta_{sf,opt} - \frac{Q_{rec,loss}}{A_{sf}\, I_{b,n}}\right)\eta_{sf,other}$$

$$\eta_{sf,opt} = \sum \left(\cos\theta_{hel} \times \eta_{hel,atm} \times N'_{hel,z}\right) \times \eta_{hel,refl} \times \eta_{rec,refl} \times \eta_{rec,spill} \times \eta_{shbl}$$



CSP plant models: description (III)

- Power cycle efficiency
  - ✓ through correlation

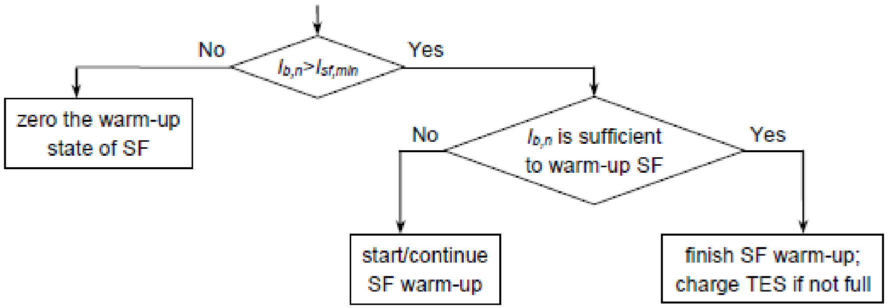


- Parasitic losses
  - ✓ variable components are found by scaling

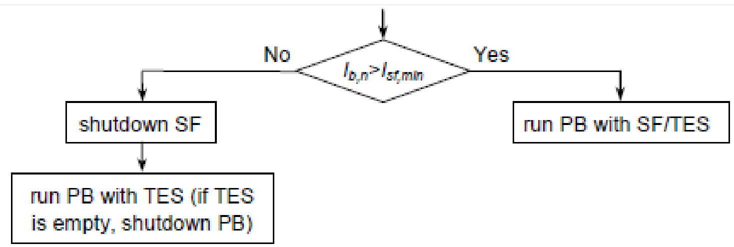
$$PL_{csp} = PL_{csp,fix} + PL_{csp,track} + PL_{csp,night} + PL_{csp,p1} + PL_{csp,p2} + PL_{csp,other}$$

CSP plant models: description (IV)

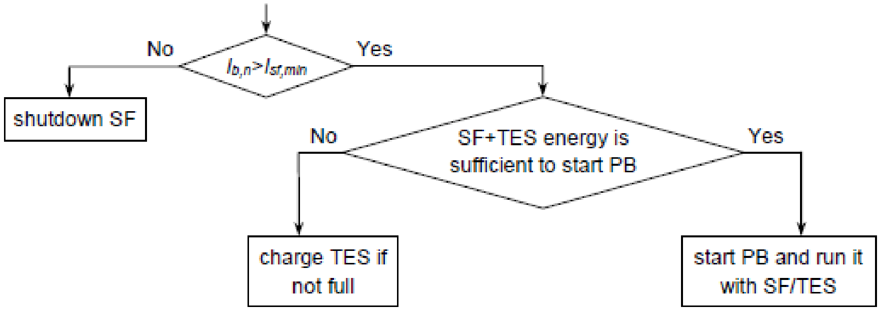
- Plant control (similar to dispatch strategy in SAM)



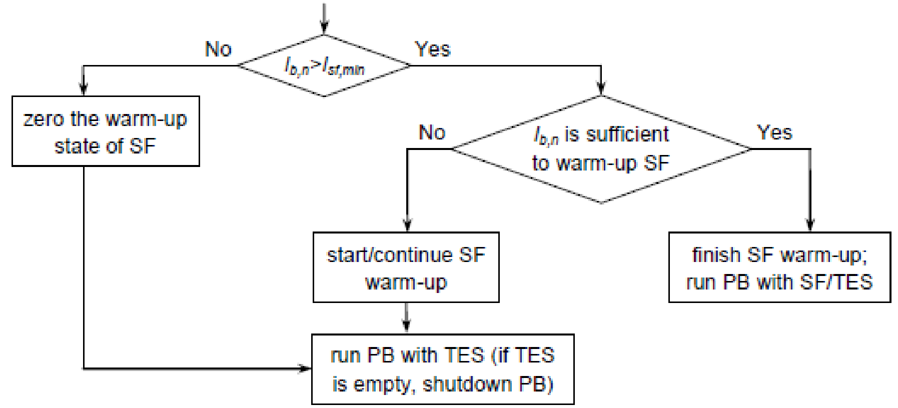
(a) SF - off, PB - off



(c) SF - on, PB - on



(b) SF - on, PB - off



(d) SF - off, PB - on

CSP plant models: validation (I)

- Comparison with SAM simulations
- Fictitious CSP plants of 111MWe
  - ✓ Scenarios: a) SM=2, TES=6; b) SM=2.5, TES=15
  - ✓ Technology: LS3, UVAC3 (trough), ext. receiver (tower)
  - ✓ Selected input parameters:

Trough

$I_{b,des} = 900W/m^2$

$T_{amb,des} = 25C^{o}$

$\eta_{ptr,max} = 74.82\%$

$\eta_{ptr,des} = 72.15\%$

$\eta_{sf,other} = 100\%$

SF density =0.383

$Q_{sf,min} = 0$

Tower

$I_{b,des} = 950W/m^2$

$\eta_{hel,refl} = 90\%$

$\eta_{rec,abs} = 94\%$

$\eta_{rec,spill} = 98\%$

$\eta_{sf,other} = 100\%$

$Q_{rec,loss} = 6.5\%\, Q_{sf,des}$

$Q_{sf,min} = 25\%\, Q_{sf,des}$

CSP plant models: validation (II)

- Comparison is not straightforward ?

$$I_{b,n} \Rightarrow Q_{sf} \Rightarrow P_{csp} \Rightarrow P_{csp,net}$$

- Matching annual predictions with adjustment coefficients:

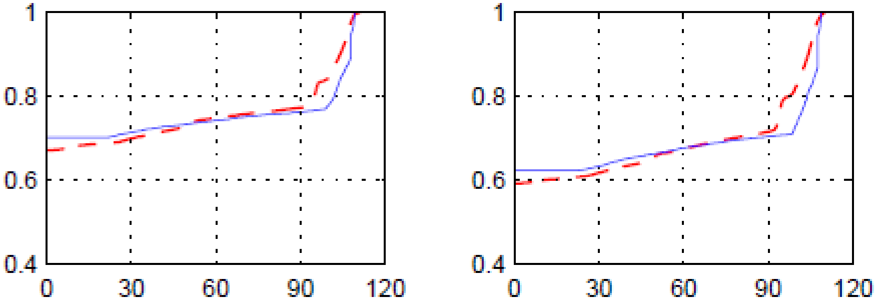
$$\begin{cases} \eta_{sf,adj} = AC_{csp1} \times \eta_{sf} \\ \eta_{pb,adj} = AC_{csp2} \times \eta_{pb} \\ PL^{des,adj}_{csp,other} = AC_{csp3} \times P_{csp,nom} + PL^{des}_{csp,other} \end{cases}$$

CSP plant models: validation (III)

- Deviations at each calculation step

	annual	monthly (summer)
$I_{b,n} \Rightarrow Q_{sf}$	5.5% (PTR), 4.1% (tower)	7% (PTR), 2% (tower)
$Q_{sf} \Rightarrow P_{csp}$	4.9%	2.6%
$P_{csp} \Rightarrow P_{csp,net}$	1.7%	0.5%

- CDFs for net production



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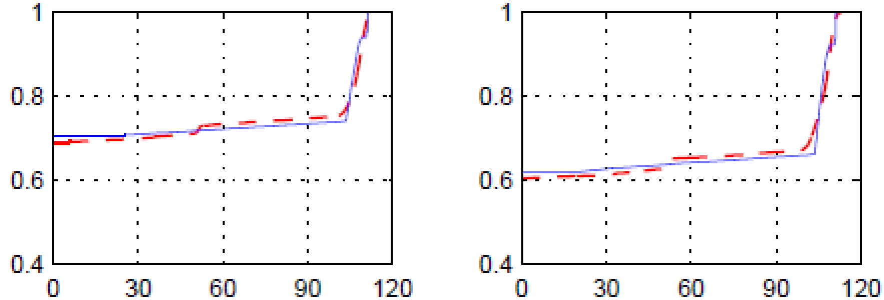
Trough



(a) Madrid (b) Seville

Tower

Solar part: conclusions and future work

- The developed solar energy models provide a good balance between accuracy and complexity

- Focus of future studies:
  - ✓ Correlation of solar radiation between sites
  - ✓ Correlation between solar and wind production
  - ✓ Improvements to plant models (effect of ambient temperature, dispatch strategy)

Thank you for your attention!

Questions or comments?