



# Combining CCS with renewable energy

Metrics of integrating CSP plants  
with fossil fueled CCS

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# Incentives



- CCS is an interim solution limited in duration by availability of fossil fuels and underground storage space
- CCS uses more fuel and hence increases dependence on fossil fuel resources
- CCS investments are seen as competing with those in renewable energy.
- However renewable energy alone cannot deliver GHG emission reductions in time.



# Advantages of integration



- Part of CCS scheme investment could be used to assist development of market for renewable energy sources
- CCS plants may be able to share a range of essential facilities with renewable energy generation
- CCS plants designs and layouts could be modified to leave a more useful legacy for sustainable renewable energy generation



# Opportunities for integration



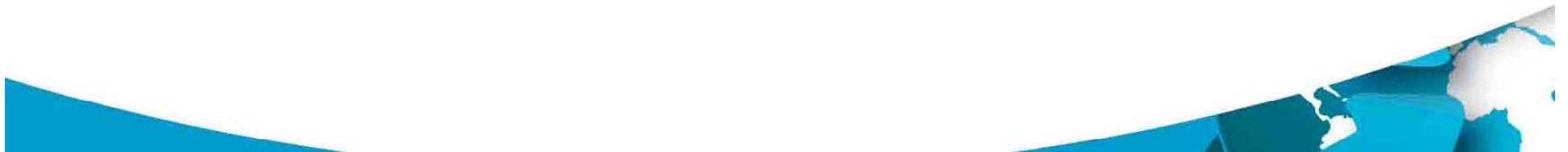
- Brainstorming ideas:-
  - Use concentrated solar thermal to provide heat for steam coal plants with CO<sub>2</sub> capture
  - Use hydrogen generated in a CCS plant as
    - a) back up fuel for concentrated solar thermal power generation
    - b) Fuel for CAES expansion turbine
  - Provide common hydrogen storage for peak smoothing for use by pre-combustion capture and renewable power generators
  - Co-firing of biomass
  - Regeneration of solid CO<sub>2</sub> sorbents



# Focus of this presentation



- CSP combined with post combustion CCS



# CSP and post-combustion CCS



- Analysis steps
  - Thermal energy requirements of CCS plants
  - Identification of streams for heating
  - Area available and required for solar thermal arrays
  - Comparison of renewable alternatives
  - Types of array and capabilities
  - Heat transport and energy storage considerations
  - Matching array type, transport medium and heat requirements
  - Effects on overall efficiency
  - Spatial layout of CCS plant and arrays

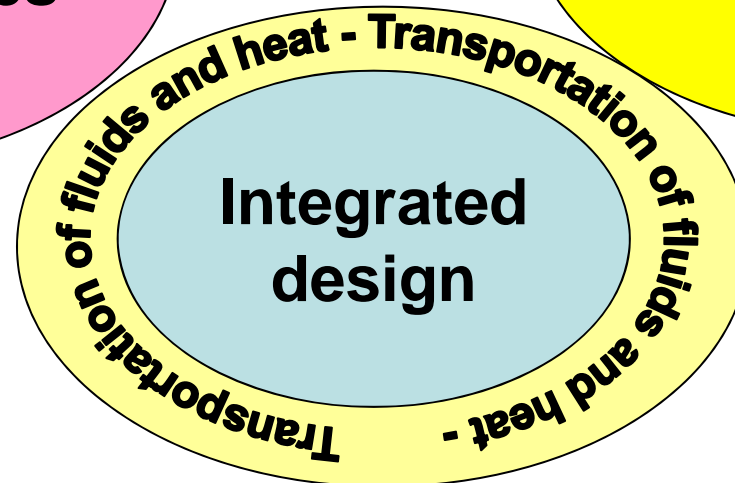


# Analysis



**CCS plant  
characteristics**

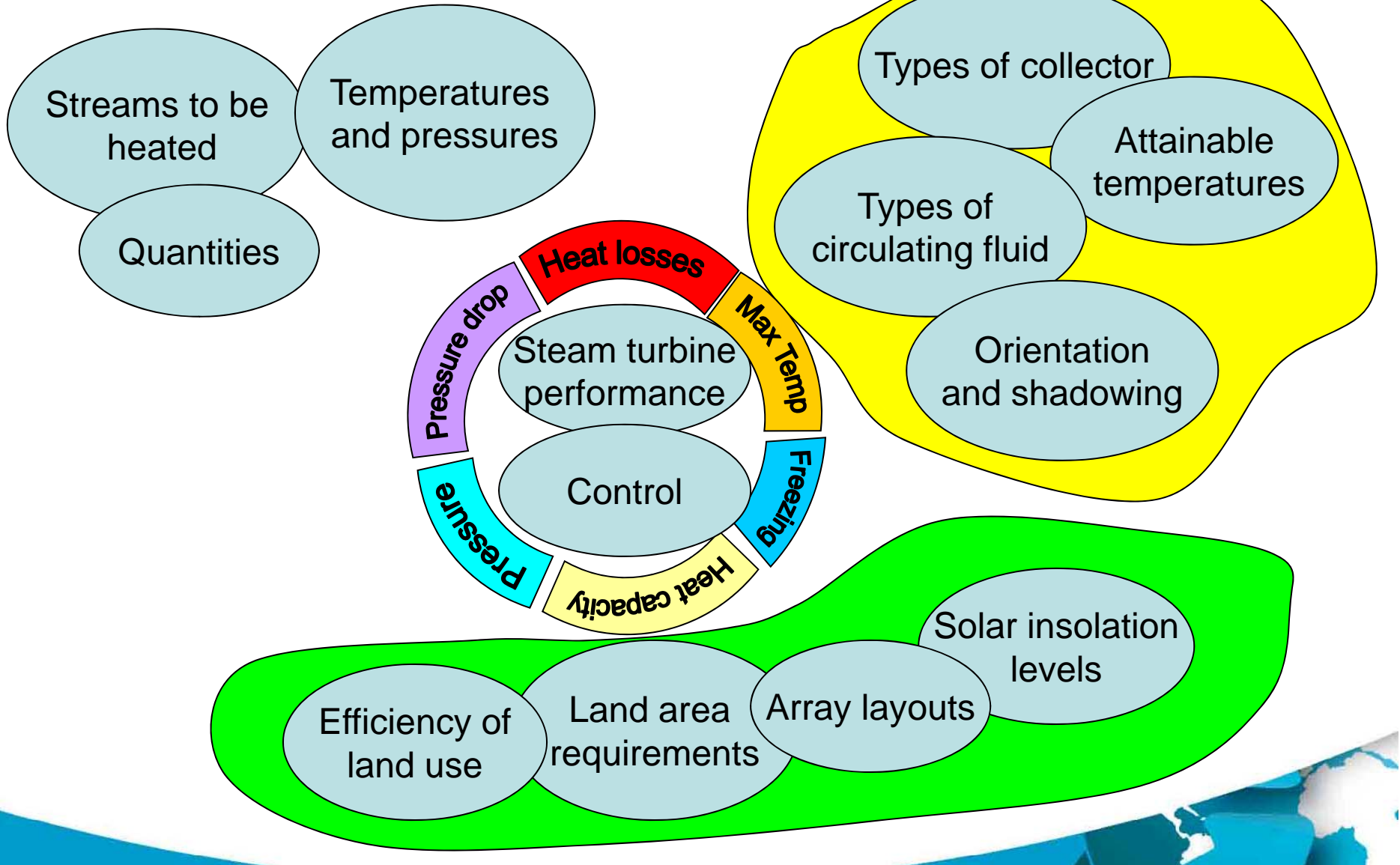
**CSP collector  
characteristics**



**Site geography**



# Matching Processes





# Streams to be heated



Stream	Temp trajectory Deg C	Fluid	Heat source displaced	Thermal duty % of total	Power conversion efficiency
Preheated BFW to main boiler	250-600 	Water → supercritical steam	FG in radiant and convection	~80% 	~45%
Steam to superheater	450-600 	Supercritical steam	FG in convection	~10% 	~45%
IP steam for reheat	300-600 	Steam at ~40bara	FG in convection	~18-20% 	~45%
LP steam for BFW heating	35-190 	Water at ~15bara	Extracted LP steam	~15% 	7-20% av 14%
IP steam for BFW heating	190-250 	Water at ~30-250bara	Extracted IP steam	~12% 	27-37% av 33%
Cold inlet air	Amb-300 	Air at 1 atm	Cool FG ex convection	~12% 	~45%
LP steam for solvent regeneration	130-140 	LPsteam	Extracted LP steam	~25% 	~20%

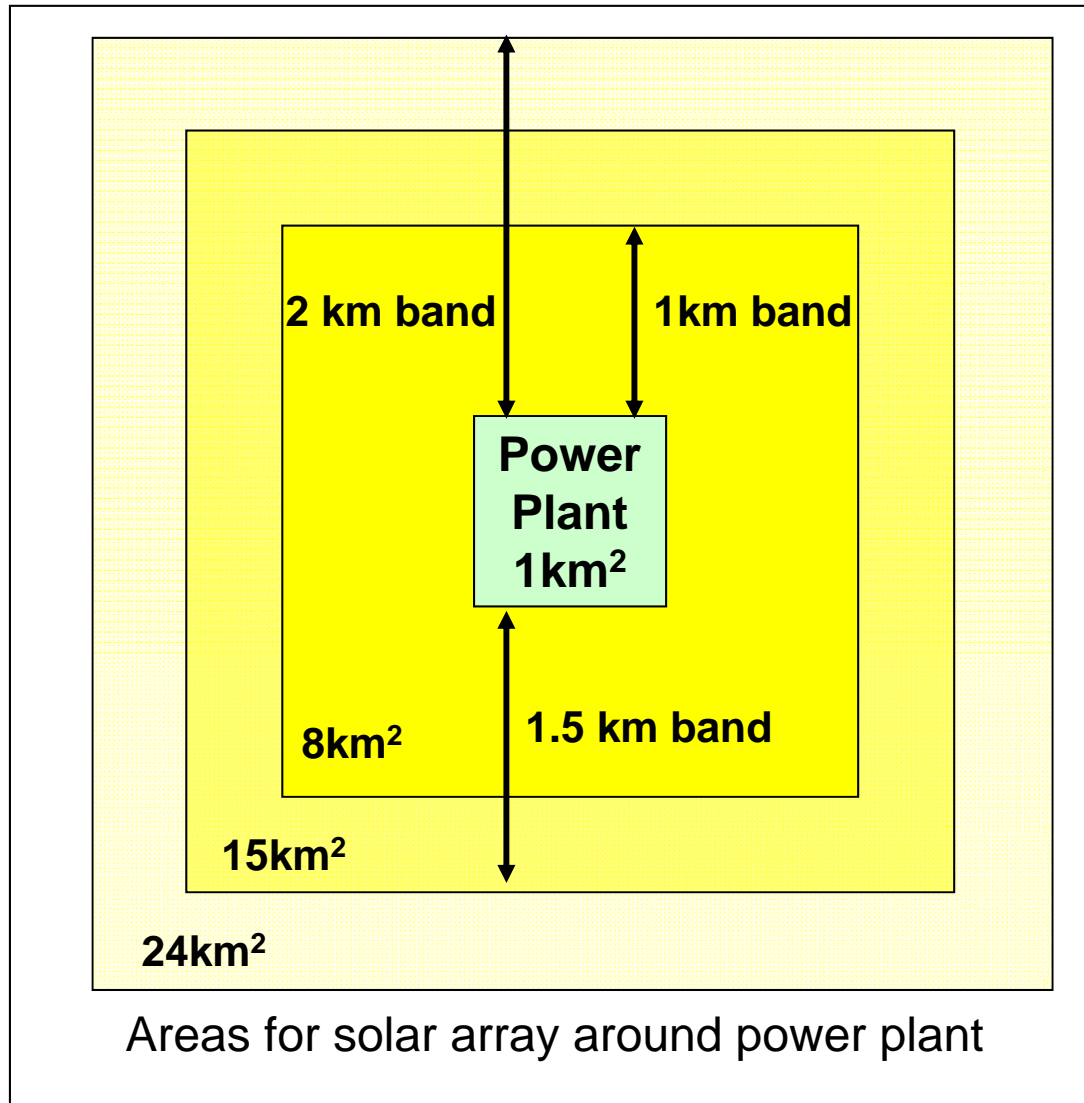
# Solar heat collection fluids



Fluid	P & T Typical range	Max ht Cap‡	Density kg/m <sup>3</sup>	Line size*	Key Limitations
Hot water	To 60barg To 290C	278	730	20in	Low temp
LP steam	2-5barg 120-165C	630	3.7	38in	Pressure drop
MPsteam	20-50barg 200-600C	845	12.7	22in	High pressure
HP steam	100-200barg 300-600C	815	55	16in	Very high pressure
Hot oils	5-10barg 100-370C	140	800	22in	Thermal degradation, H <sub>2</sub> invades vacuum
Molten salts	5-10barg >130-540C	150	1680	16in	High freezing temperature

‡ Cal /gm assumes typical return temp    \* Approx size for 100MWe equivalent 2bar/km

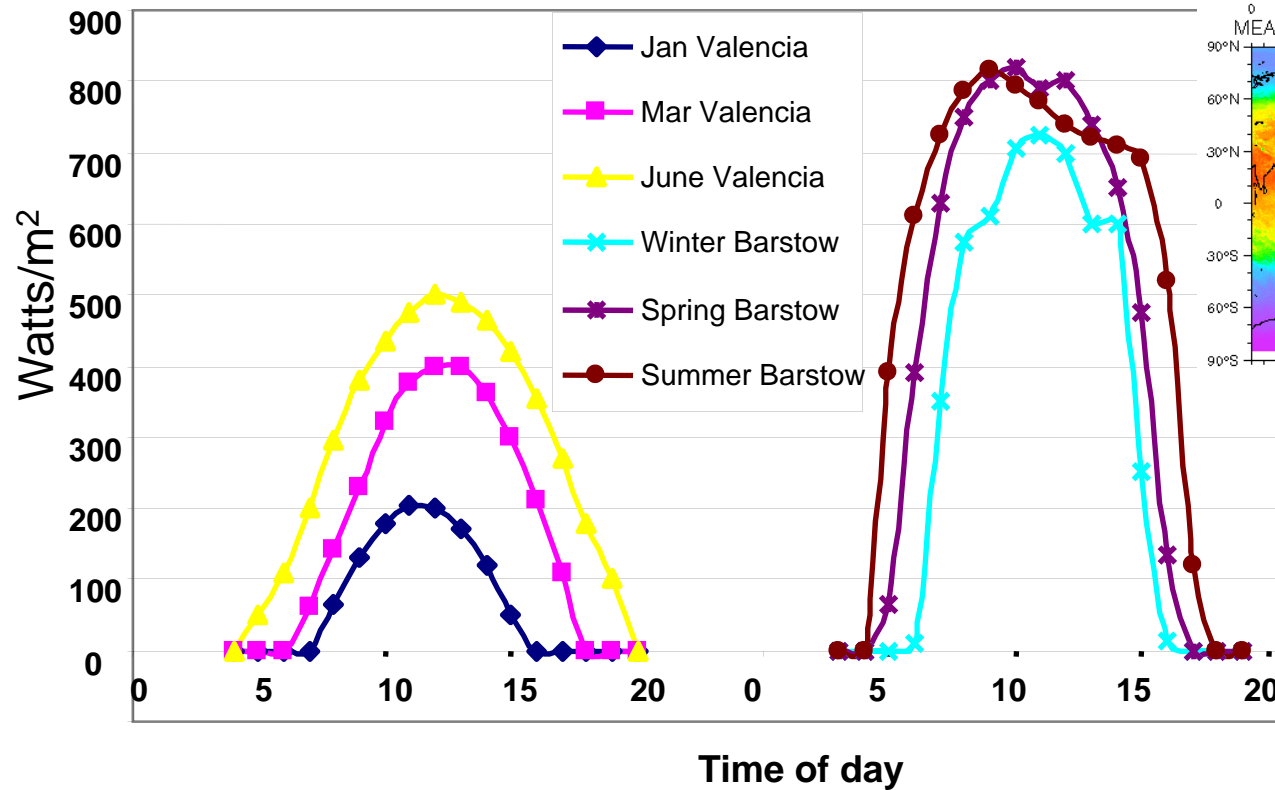
# Relative areas around plant



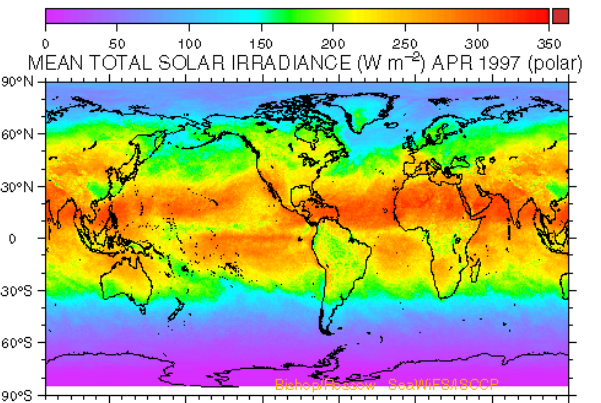
# Typical daily solar irradiance



## Typical solar irradiance - Valencia island Met station SW Ireland and Daggett-Barstow, California



ISCCP SOLAR IRRADIANCE DATA CONTEMPORANEOUS WITH OCTS



# Types of concentrated solar power array



parabolic trough (PSA)



solar tower (SNL)



Ivanpah boiler



linear Fresnel (Solarmundo)



parabolic dish (SBP)

Sources (DLR,SNL, Solarmundo,SBP)



# Types of solar thermal array



Type	Concentration factor	Shading effects	Other characteristics
Flat plate	None	Minimal	Low cost, no tracking needed
Linear parabolic	70-80	Moderate	Single axis tracking
Fresnel linear	25-100	Moderate	Single axis tracking
Central tower (HT)	300-1000	Major	Dual axis tracking
Parabolic dish (HT)	1000-3000	Major	Dual axis tracking

# Consider some alternatives



Method	Collection efficiency	Area useable	Conversion to AC power	Relative power
Biomass Low yield	.3%	80%	45%	2.1
Biomass high yield	.8%	80%	45%	5.5
PV high eff	15%	70%	90%	180
PV low eff	10%	70%	90%	120
CSP low temp	30%	70%	25%	100
CSP high temp	30%	30%	40%	69

# Power densities



- 1GW power station ----- Occupies  $\sim 1\text{km}^2$ 
  - Electric power density =  $1000\text{w/m}^2$
  - Thermal power density =  $2222\text{w/m}^2$
- Solar insolation ( $1.5\text{km}$  band =  $15\text{km}^2$ )  
Design range peak insolation  $500\text{-}1000\text{w/m}^2$ 
  - Average insolation\*  $100\text{-}250\text{ w/m}^2$
  - **Max continuous available =**

**$1500 - 3750\text{MW}_{\text{thermal}}$**

*\* 100 Typical for UK locations, 250 typical for prime solar locations*



# Power densities continued



- Useable collection area 20% - 80%
  - Thermal collection efficiency 30% - 50%
- HENCE Thermal collection efficiency 6% - 40%**

- Power conversion efficiency 30% - 15%
- HENCE Incident solar to electric power 2% - 6%**

**THUS Effective power density: temperate = 2 – 6 w/m<sup>2</sup>**  
**prime = 5 – 15 w/m<sup>2</sup>**

**THUS Max renewable generation**  
**Temperate location = 30 - 90MWe**  
**Prime location = 75 - 225MWe**

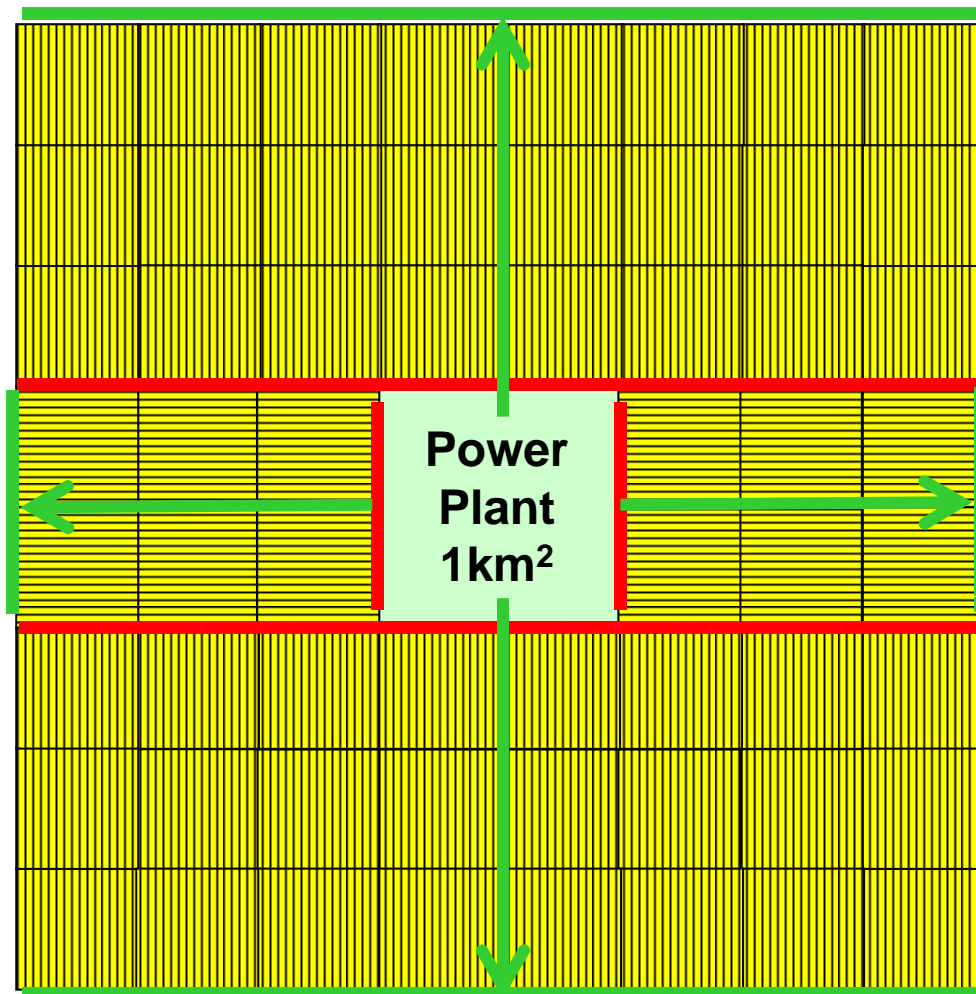
# Matching peak supply



Peak solar intensity	1km collection band	1.5km collection band	2km collection band
500w/m <sup>2</sup>	830 MW <sub>th</sub>	1560 MW <sub>th</sub>	2500 MW <sub>th</sub>
1000w/m <sup>2</sup>	1660 MW <sub>th</sub>	3120 MW <sub>th</sub>	5000 MW <sub>th</sub>

Duty to be replaced	MW thermal
LP steam for BFW heating	430MW
IP steam for BFW heating	340MW
LP steam for solvent regeneration	750MW
<b>TOTAL</b>	<b>1520MW</b>

# Array orientation and headers



N-S Arrays



E-W Arrays



Steam header 10km



Water header 16km

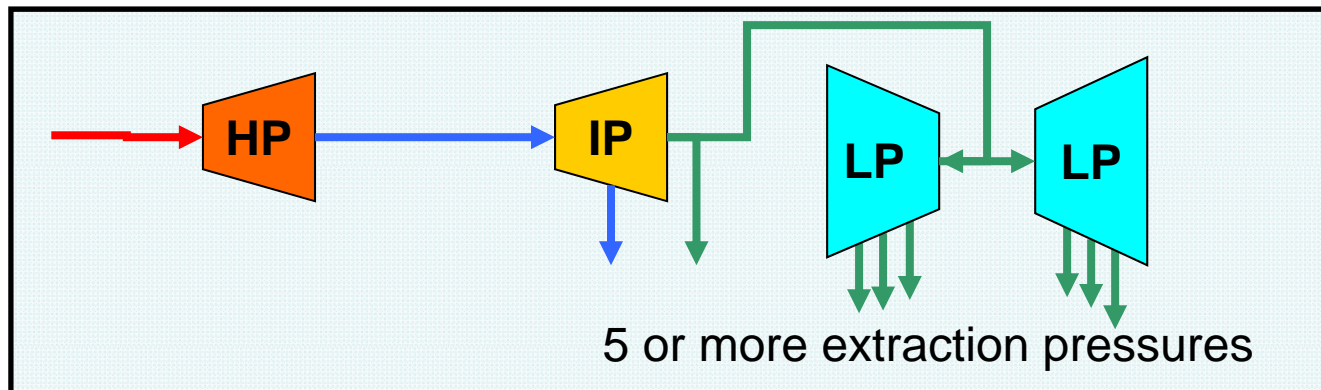
60 squares of .25km<sup>2</sup>  
=15km<sup>2</sup>



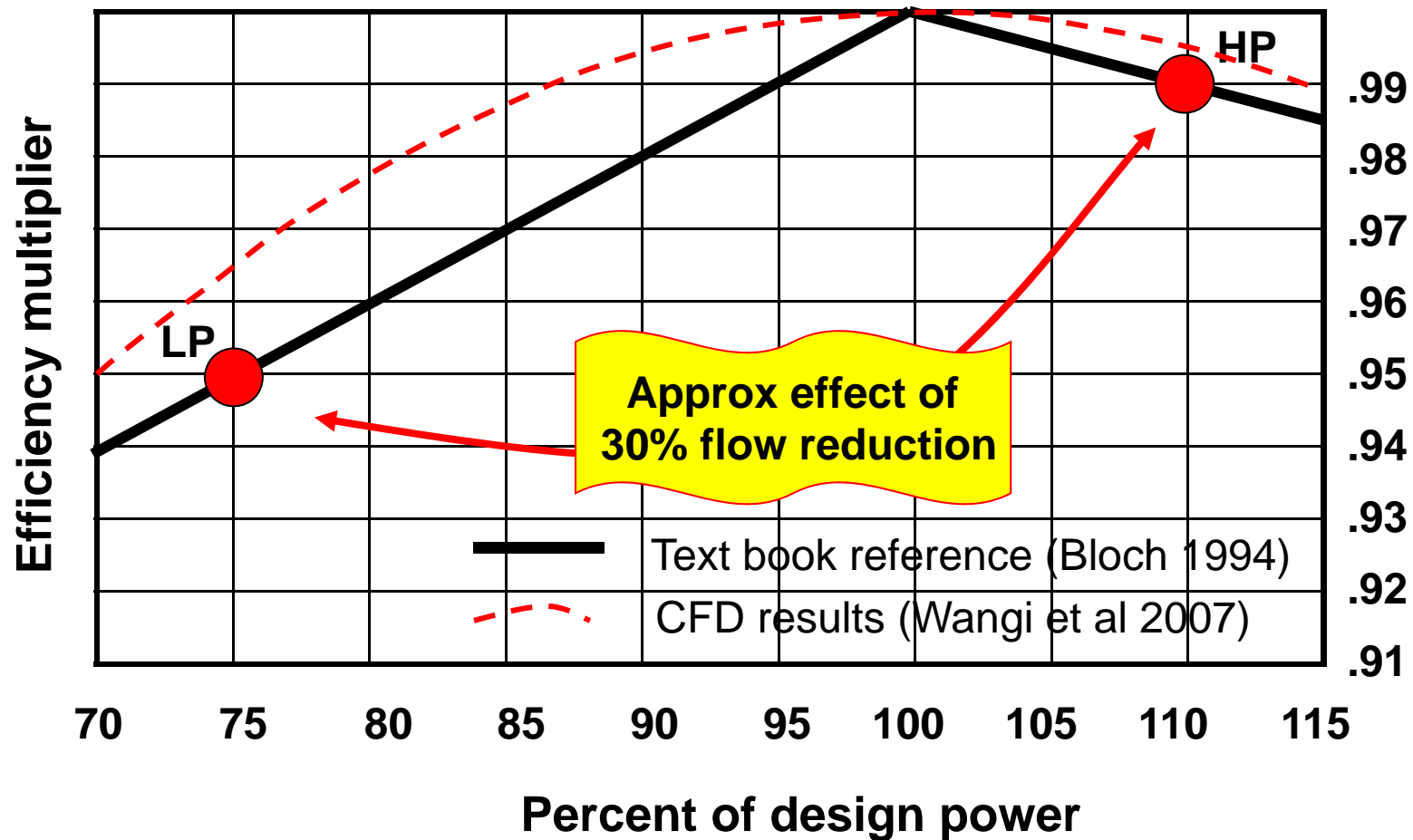
# Steam turbine performance



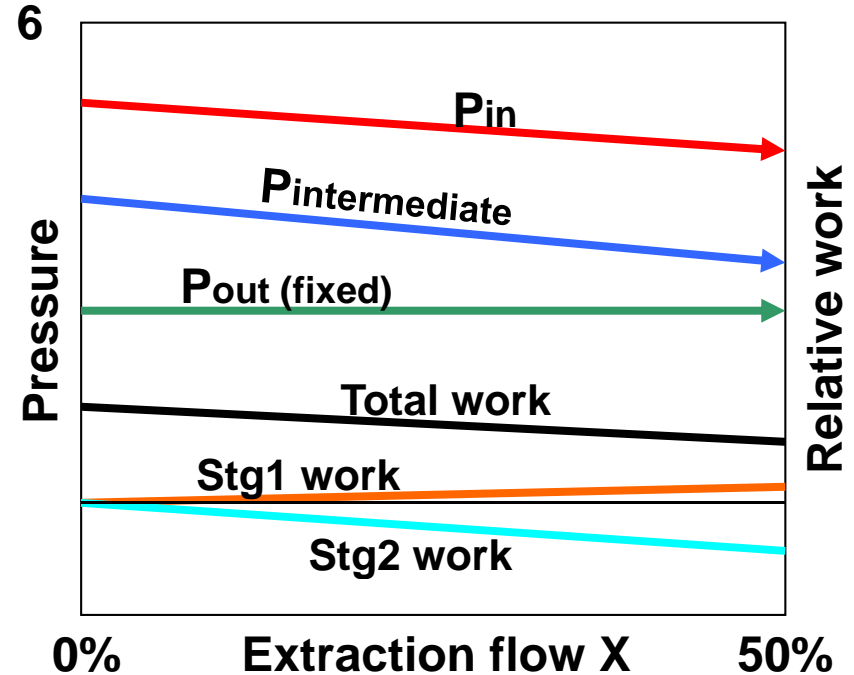
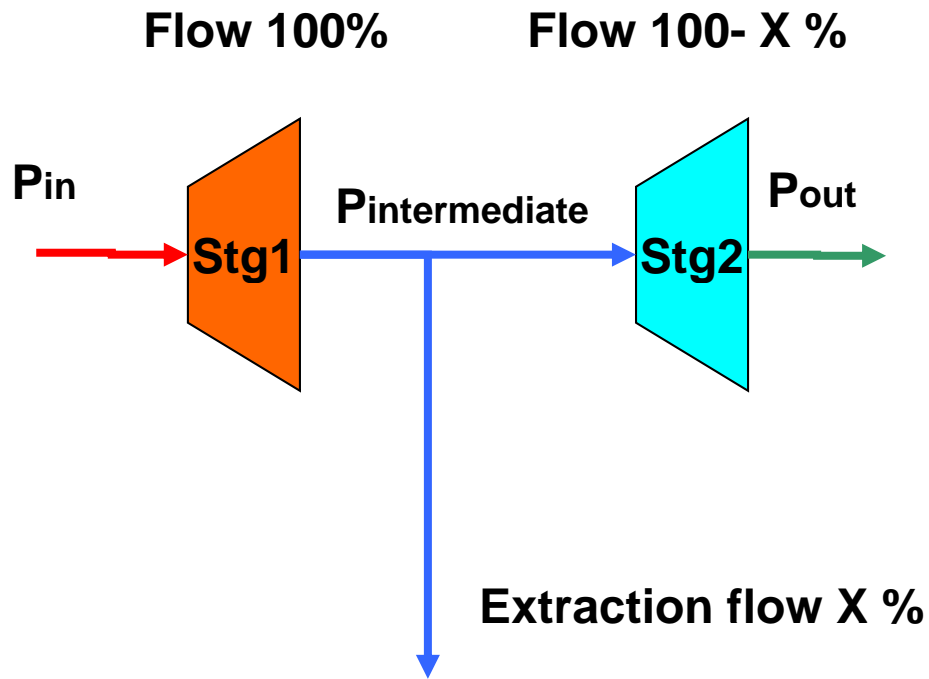
- Steam turbines in Power plant operate at constant speed
- Maximum efficiency is with design point volume flows at every stage
- Efficiency falls off for higher or lower flows  
*(Steam no longer enters stages at optimum angle)*
- Higher flows cause increased blade stress



# Effects of flow change on ST efficiency



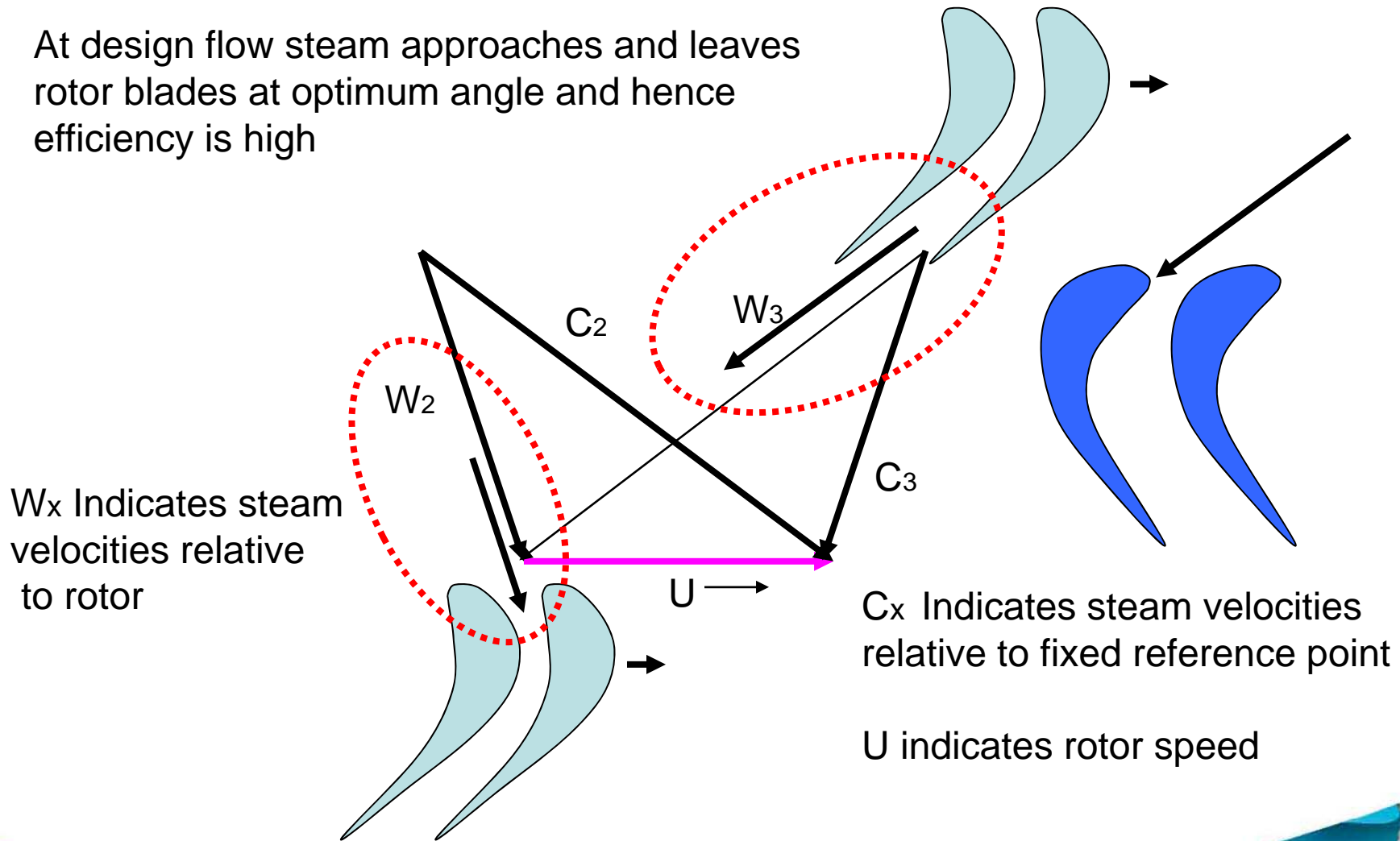
# Effects of extraction flow changes



# Velocity triangles



At design flow steam approaches and leaves rotor blades at optimum angle and hence efficiency is high



$W_x$  Indicates steam velocities relative to rotor

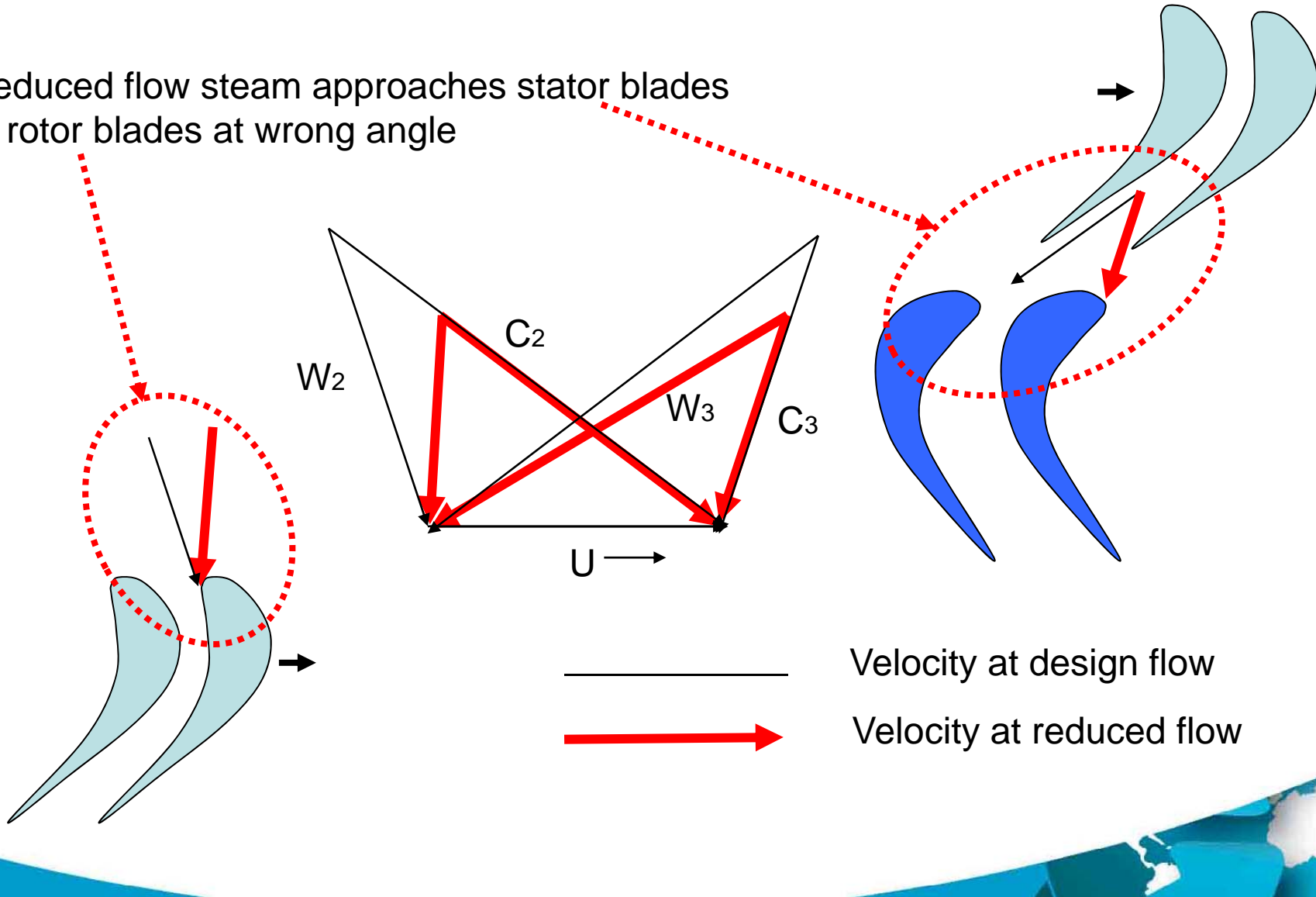
$C_x$  Indicates steam velocities relative to fixed reference point

$U$  indicates rotor speed

# Velocity triangles

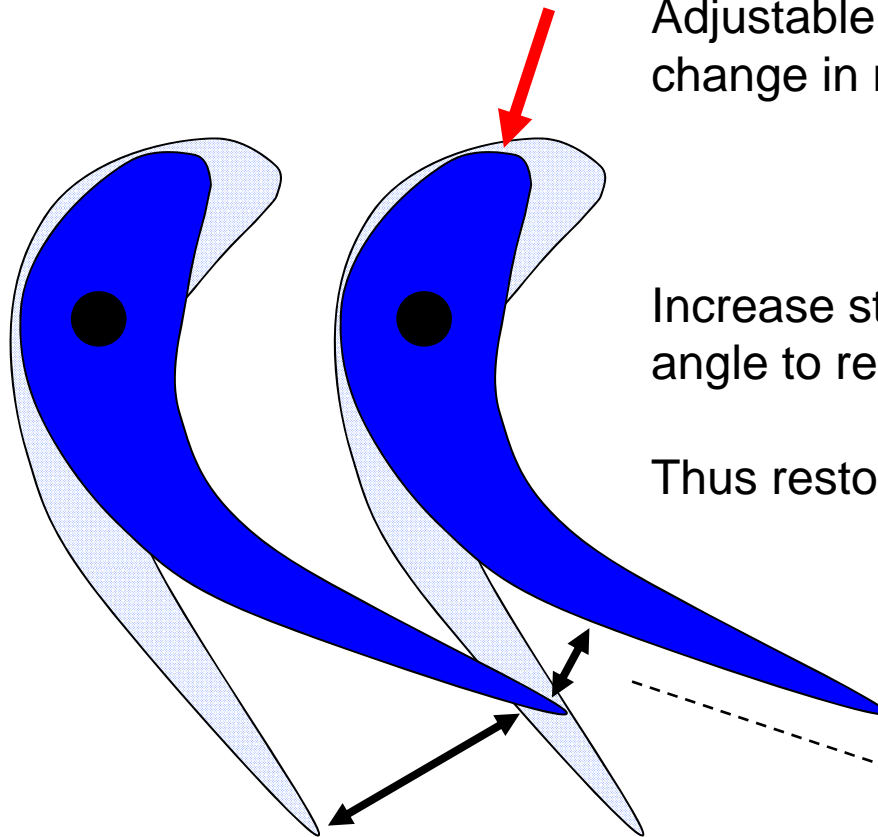


At reduced flow steam approaches stator blades and rotor blades at wrong angle





# Adjustable stators?

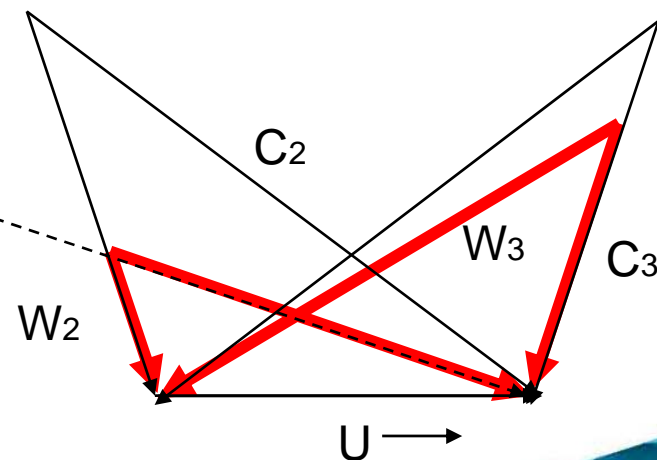


Adjustable stators could accommodate change in rotor exit direction

And

Increase stator exit velocity / alter exit angle to restore flows to optimum direction

Thus restoring lost efficiency



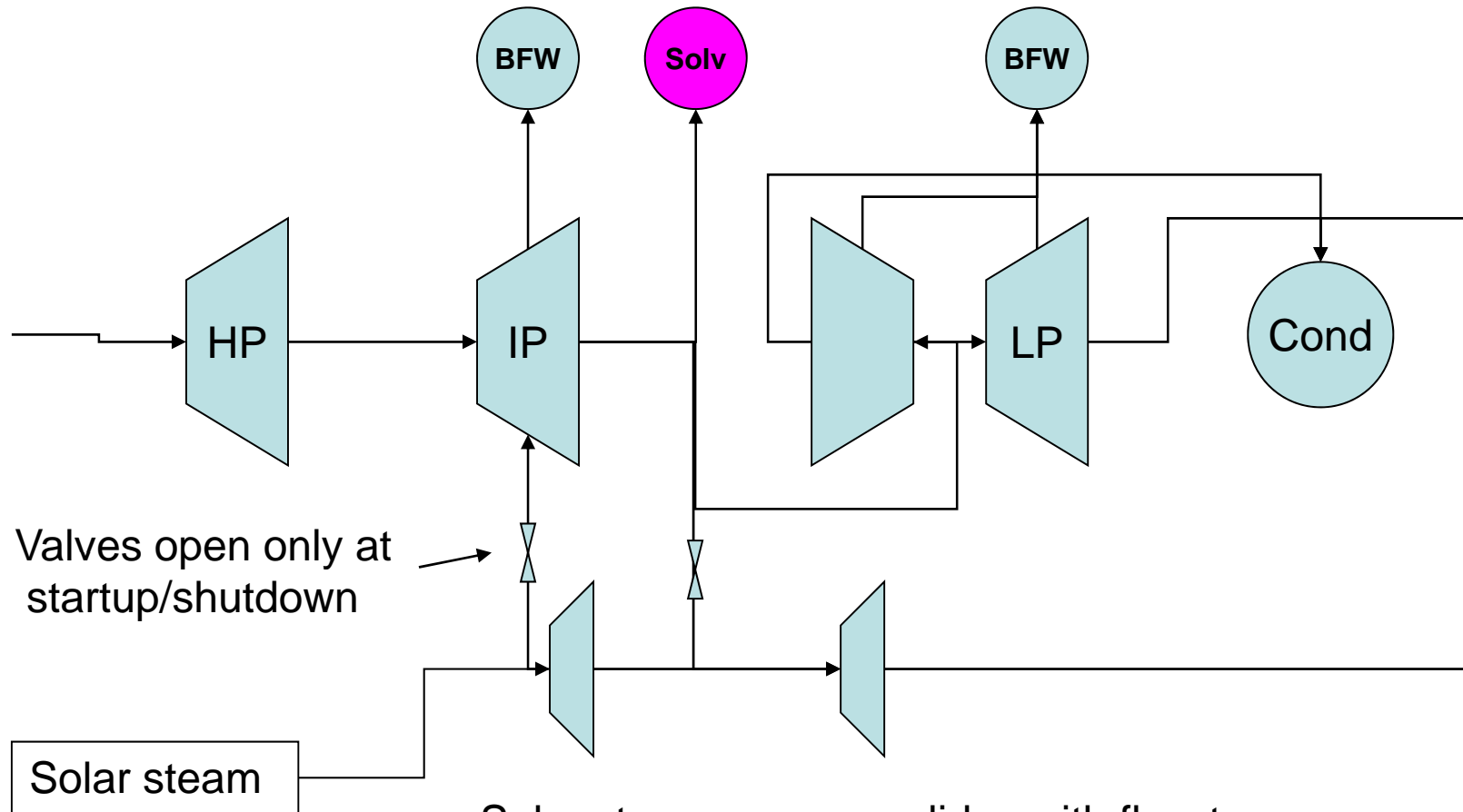
# Consequences



- Some steam turbine stages would have to run most of time at low capacity  
*i.e when solar energy not available*
- Resultant efficiency loss would reduce advantages of efficient conversion in large machines.
- A solution is to have separate turbine for solar steam flows.
- Another future solution might be use of variable geometry stator blades



# Tie in of solar steam turbines



Valves open only at startup/shutdown

Solar steam

Solar steam pressure slides with flow to maximise turbine efficiency



# Other benefits



- Solar steam turbine can be used to absorb extracted LP steam if CO<sub>2</sub> capture is temporarily stopped
- Consider splitting solar turbine into 2 machines so that swallowing capacity of one can match this.
- Splitting into two machines will improve overall efficiency outside peak solar insolation



# Conclusions



- Area around a large CCS plant is sufficient to collect significant amount of solar thermal energy
- Direct steam generation using linear Fresnel arrays makes best use of the land
- Best use of the energy is through installation of a separate steam turbine system
- This would leave a permanent stand alone legacy of a small independent solar power plant



# Acknowledgements



- IEA Greenhouse Gas R & D Programme
- An IEAGHG report on this work is currently being finalised





**Thank you**