CSP PLANT OPERATIONS & MAINTENANCE

Middle East & North Africa Concentrating Solar Power Knowledge & Innovation Program – MENA CSP KIP

WORLD BANK GROUP
هيئة كهرباء ومياه دبي
Dubai Electricity & Water Authority
CLIMATE INVESTMENT FUNDS
CTF CLEAN TECHNOLOGY FUND

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Fraunhofer Institute for Solar Energy Systems ISE

2nd MENA CSP KIP Workshop “CSP Markets, System Value & Financing”

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Hyatt Regency Creek Heights
Dubai

Training Courses on Concentrating Solar Power

Benefits of CSP Training Courses

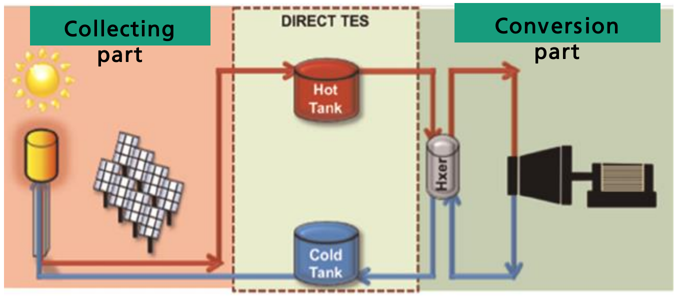
- ✓ **Make informed decisions about CSP** and draw your own conclusions on this technology
- ✓ **Learn from experts**, we have assembled a team of first-class professionals in CSP technology, policy, and energy modelling to deliver these courses
- ✓ **Learn only what is relevant to you**: deepen your knowledge on the aspects of CSP that are useful to you without having to learn about topics that are not applicable to you
- ✓ **Save time**: obtain all the information you need about CSP in one training course delivered at a convenient location
- ✓ **Professional development**: expand your education on energy with these training courses
- ✓ **Free of charge**: the CSP Training Courses are fully supported by the World Bank so you will obtain excellent training at no cost to you or your organization

The World Bank's MENA CSP Knowledge and Innovation Program brings to you fully customized training courses that will enable you to further your understanding of Concentrating Solar Power (CSP) technology, cost modelling and related policy issues.

OUTLINE

(A GLIMPSE INTO 2 CSP TRAINING SESSIONS)

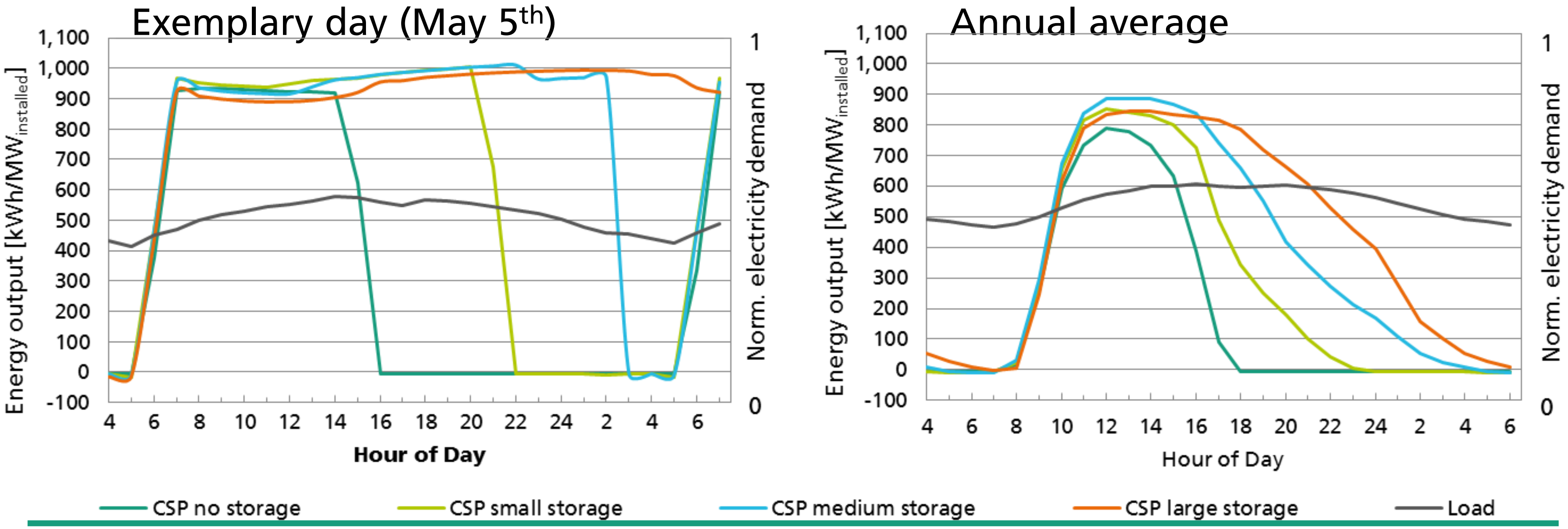
- **CSP Plant Operating Strategies**
  - Operating strategies from EPC / Utility / Planner perspective
  - Typical plant operation strategies: solar-driven, peak production strategy, and reduced stops
  - Importance of DNI Forecast
- **Integrated Water Management in CSP Plants**
  - Water demand of the cooling system
  - Water demand of the mirror cleaning system
  - Measurement of soiling/cleanliness



Why CSP? Case study – RE-mix at middle east site

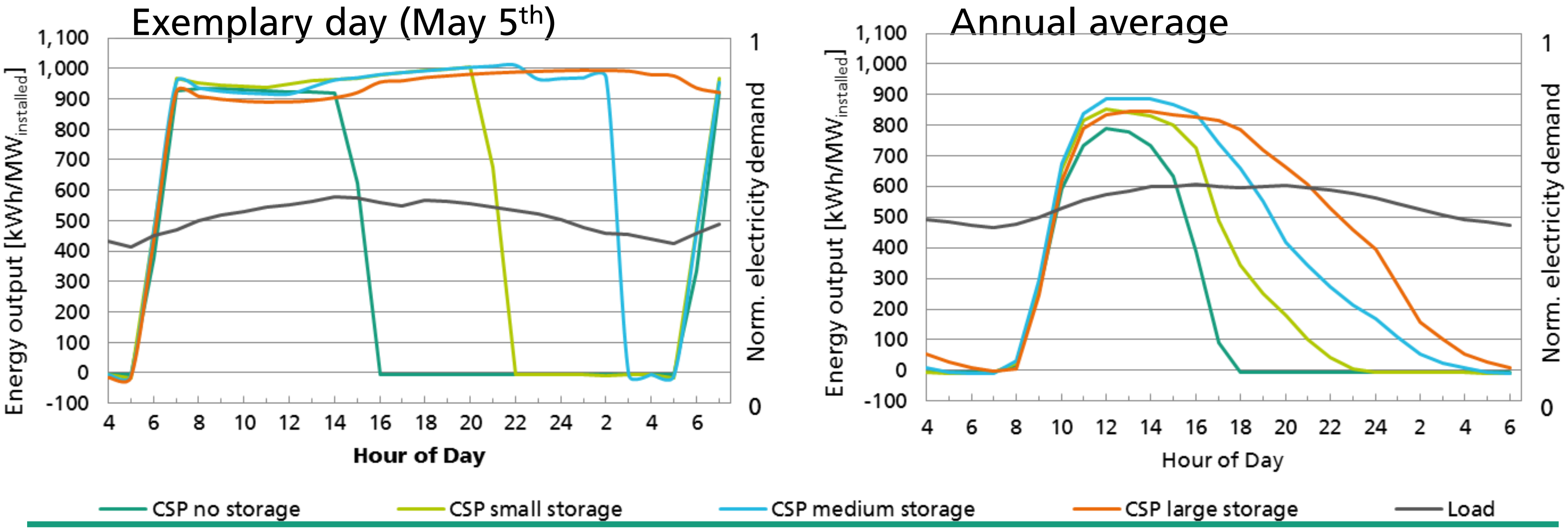
CSP production profile vs. load

- On a good solar day, CSP storages are filled and the complete period of high load can be covered
- With large thermal storage, even 24/7 operation is possible
- Annual average shows the positive influence of storage



Why CSP? Case study – RE-mix at middle east site
CSP production profile vs. load

- More storage = higher investment:
  - ➢ additional CAPEX of storage
  - ➢ + CAPEX of additional solar field to fill up storage (→ Solar Multiple)
- ➢ **How to best utilize CSP Storage?**



CSP Plant Operation - Different Actors

Planner

- Wants to plan with dispatchable storage
- System perspective: simplified models of possible operation modes

EPC

- Needs to know intended future use for design
- Easiest to design plant for peak load / solar driven operation

Operator

- Wants to get return on investment
- Bound to contract / market: PPA; FiT; day ahead market …
- detailed operation strategy + detailed forecasting of solar resource

Utility

- Wants to utilize storage for system services
- Needs to know possible operation modes
- No need for detailed forecasting ← done by Operator

Services for Commercial CSP Projects
Fraunhofer ISE

Strategy

- Technology screening
- **RE Master plans**
- R&D Roadmaps

Project Develop-ment

- Site assessment
- **Pre-feasibility**
- **Feasibility**

Engineering

- Molten salt system
- **Plant Optimization**
- Cooling concept evaluation

Procurement/ Commissioning

- Supplier assessment
- Mirror quality assurance
- Tender preparation and evaluation
- **Performance testing**

Operation

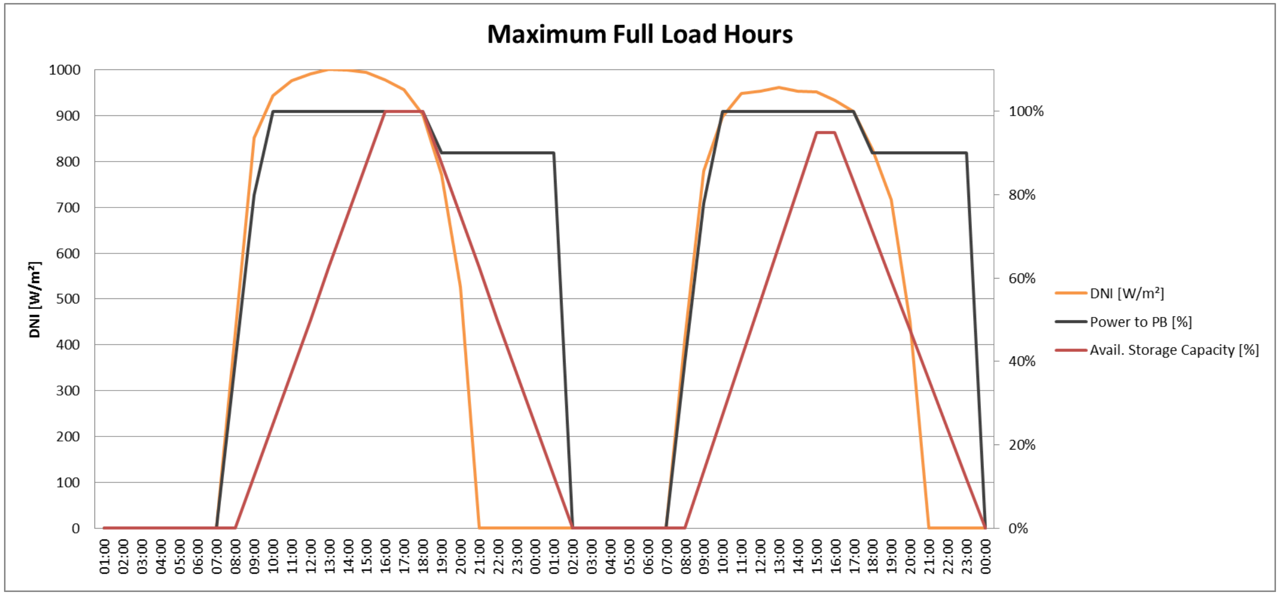
- **Plant Monitoring**
- **Operation strategy optimization**
- Mirror cleaning optimization

SOLAR DRIVEN STRATEGY

- This strategy is **the reference operation for any CSP plant**, showing the typical behavior of all renewable energy plants, since it’s aimed to **produce the maximum possible electric power** whenever there is enough resource available.
- This strategy represents the straightforward TES operation strategy, **charging the storage with the excess of solar power** once the power block is operating at full load and discharging the storage whenever the solar power is not enough to drive the power block at full load, until completely depleting it.
- This type of operation is **close to maximizing the efficiency and the energy yield** of the CSP plant.

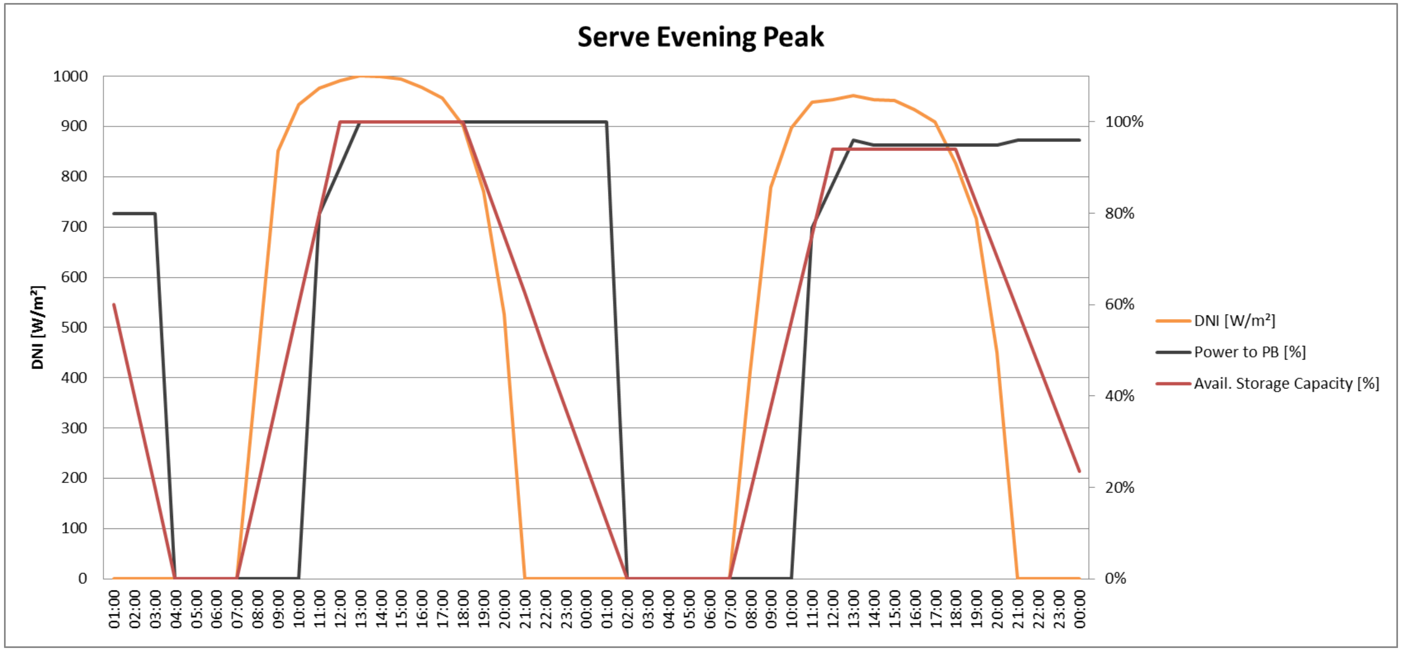
Example operating strategy
Solar driven strategy = Maximizing Full Load Hours

- run power block on full load for as long as possible
- run PB as soon as thermal energy is available
- PRO: provide more hours of 100% net energy production to grid
- CON: less remaining storage capacity at night to provide night operation
- CON: early PB stop after cloudy day(s) or in winter
- CON: longer turbine stand-by time



Example operating strategy
Serving Evening Peak

- Use storage to run on full load from storage during evening peak
- during day: fill up storage + run PB on part-load
- PRO: load curve adapted PB operation
- PRO: longer operation in night hours from storage
- CON: still turbine stand-by time



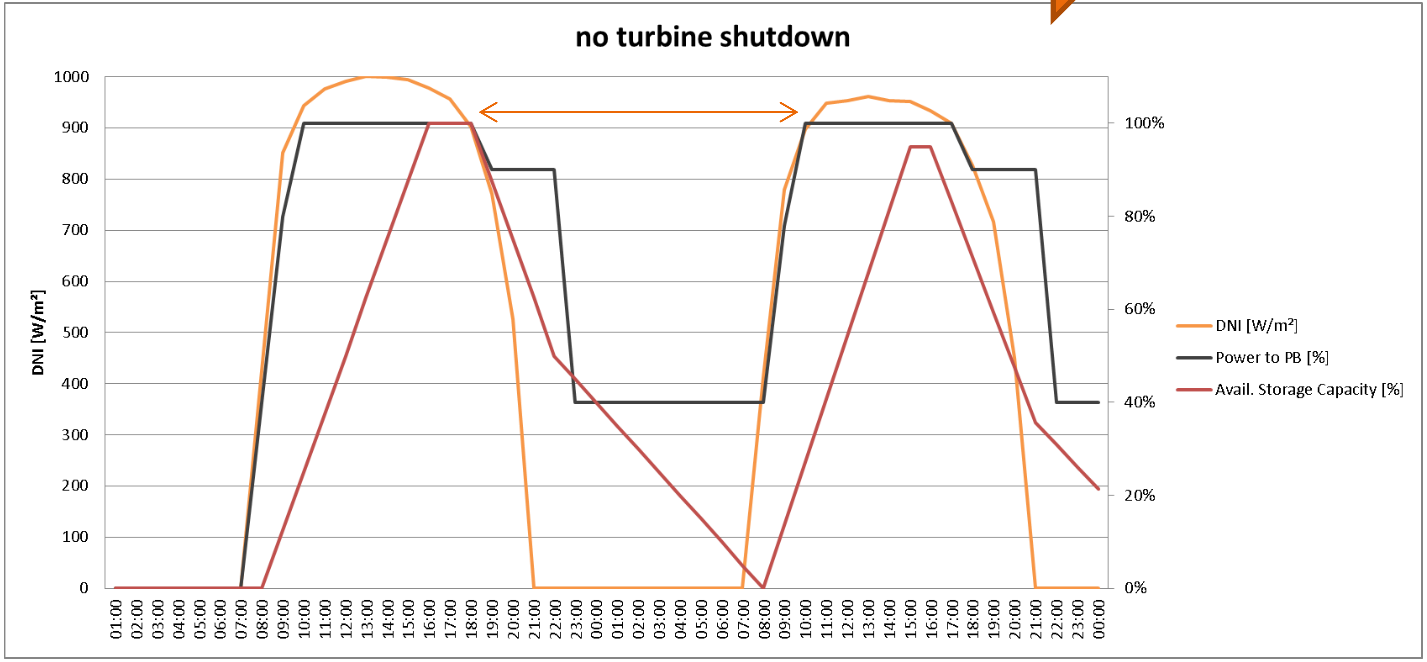
REDUCE STOPS OPERATIONAL STRATEGY

- The main goal of this strategy is to **reduce the power block stops** and, consequently, to **maximize the power block online hours**.
- This can be achieved by always ensuring certain level of energy stored in the TES while solar power is available and by discharging the storage system at reduced power block loads (therefore during longer time) while no solar power is available.

Example operating strategy
Reduce the power block stops

- during day: fill up storage + run PB on full load
- run PB continuously on low part-load at night until next morning
- PRO: less turbine stand-by hours / longer turbine life-time
- CON: difficult part-load operation during cloudy days / winter days

Forecast horizon: this day + next day



PEAK PRODUCTION OPERATIONAL STRATEGY

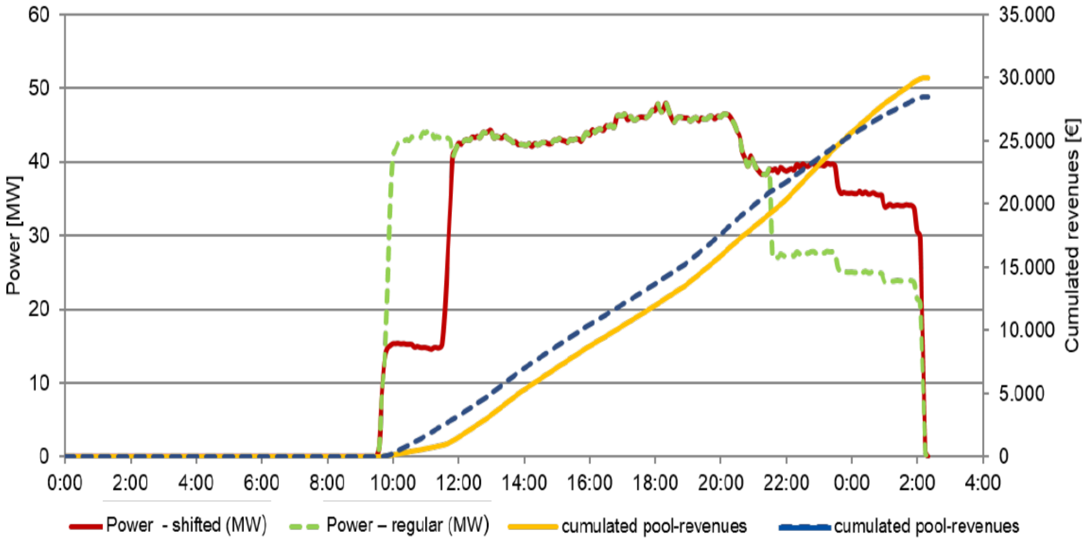
- The main goal of this strategy is to **adapt the electric energy production to a demand or energy selling price curve,** therefore increasing economic profits.

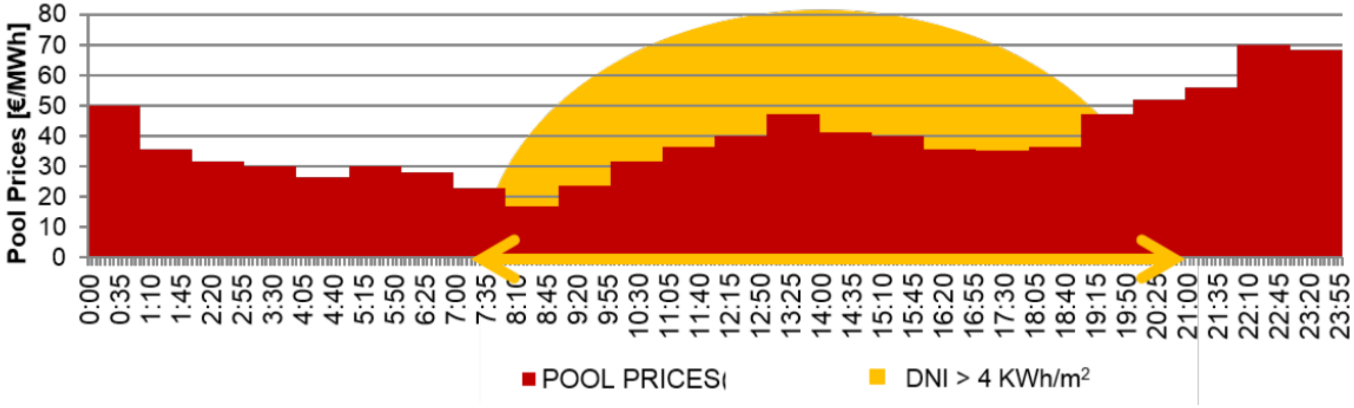
- by preferentially **charging the storage system during valley and off-peak hours and preferentially discharging it during peak (demand or price) hours.**

Example operating strategies
Motivation: load management / revenue optimization

Revenue optimization @ Pool Energy Exchange

- Plant: Andasol 3, Spain
- Example day: 1st July 2012
- Result: 5 % additional revenue due to optimized storage operation



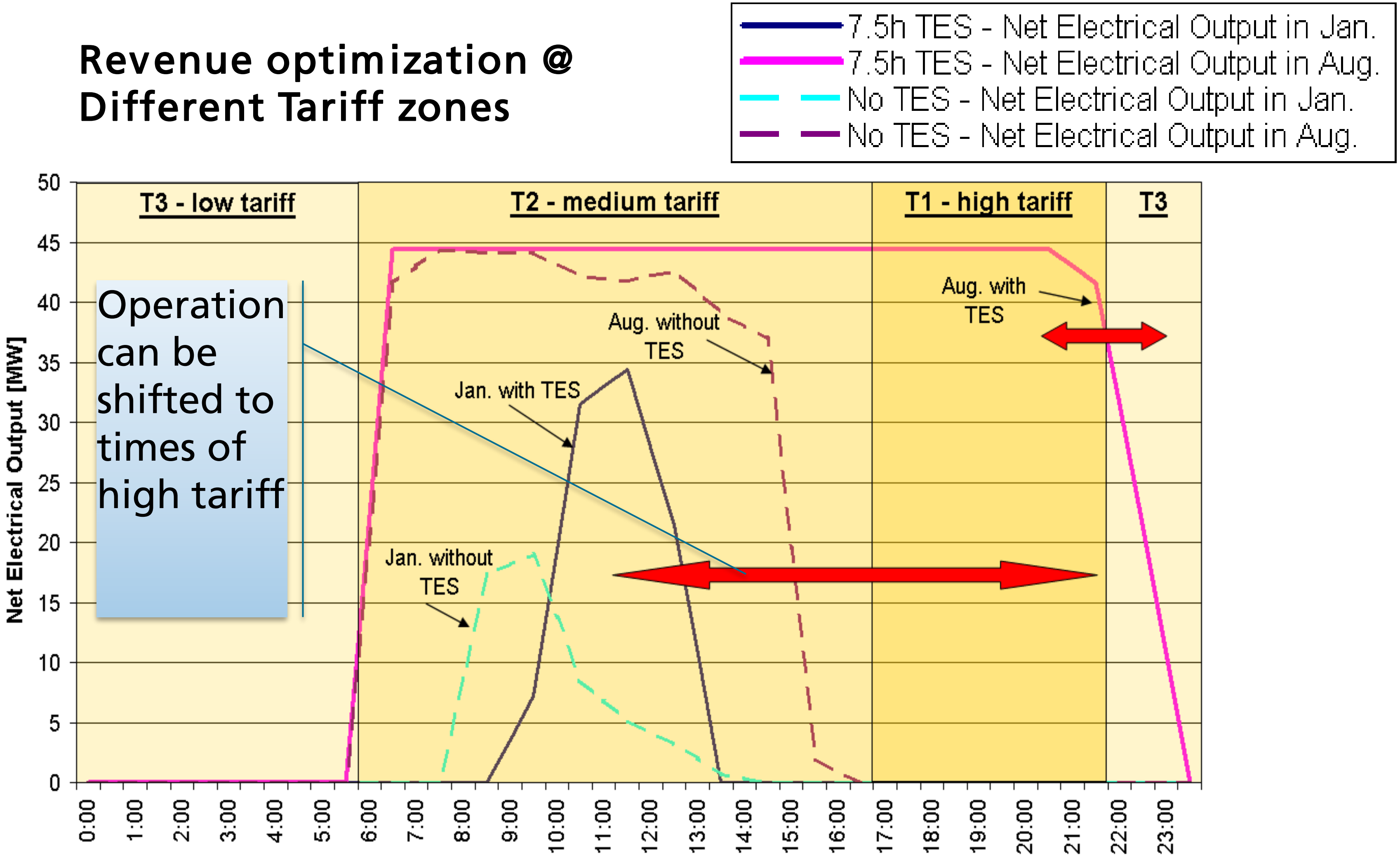


Quelle: Dinter, SolarPACES 2013

Higher revenues by load management

Production is shifted to high demand & high tariff times

Revenue optimization @ Different Tariff zones

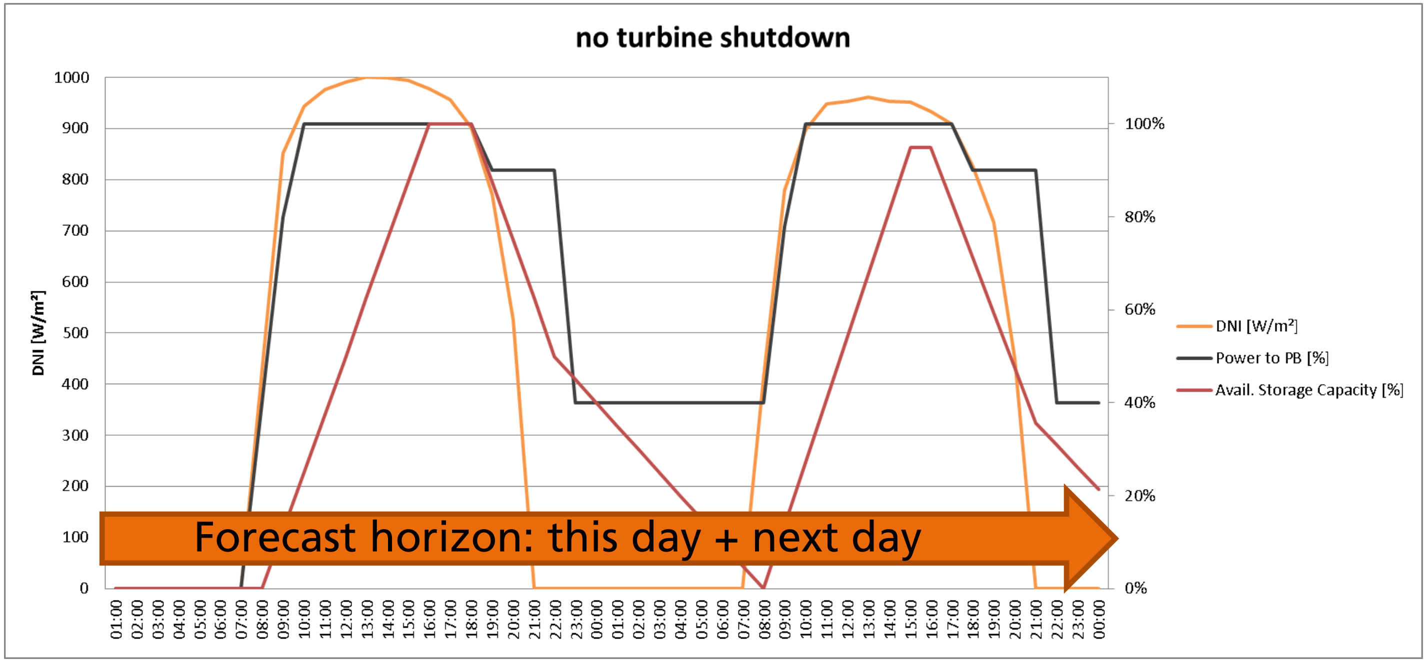


Operation can be shifted to times of high tariff

DNI forecast - Why?

- Internal
  - Stabilize Operation (<30min)
  - **Operation planning** (1h…Xdays)
  - Maintenance planning

- External
  - Peak/low demand
  - Revenue (spot market)



Forecast horizon: this day + next day

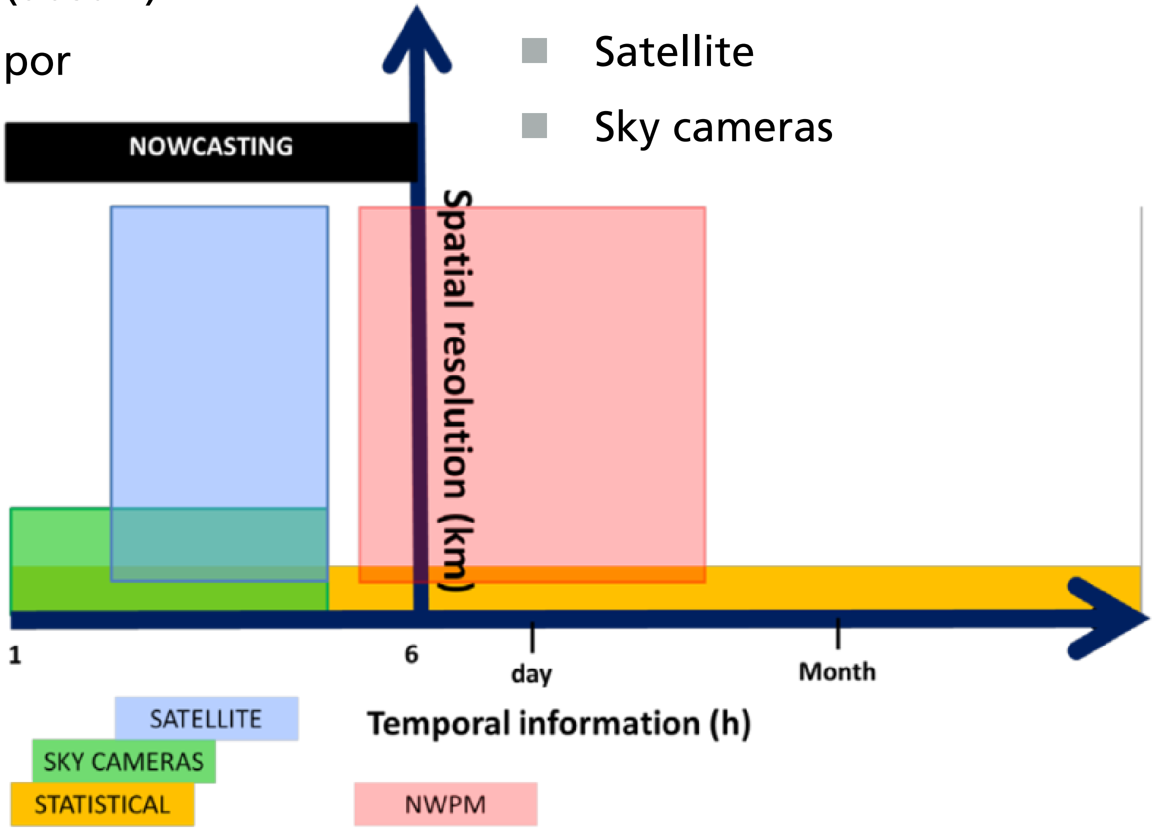
DNI forecast - Why?

Project moment	Forecast role	Typical name	Time period ahead	Main techniques	Typical time resolution
Design & assessment	Project profitability	Long term	Years	Statistical models	Months
Plant operation	Maintenance planning	Medium term	Months		Days
	Maintenance planning	10 days	Days	Numerical weather predication models (NWPM)	Half day
	Operation	3 days	Days		Hourly
	Electricity market	Nowcasting	4-6 hours		30 mins
	Stabilize operation	Nowcasting	0-6 hours	Statistical models	15 mins
	Stabilize operation	Nowcasting	0-120 mins	Satellite image	15 min
	Stabilize operation	Nowcasting	0-60 mins	Sky cameras	1 min

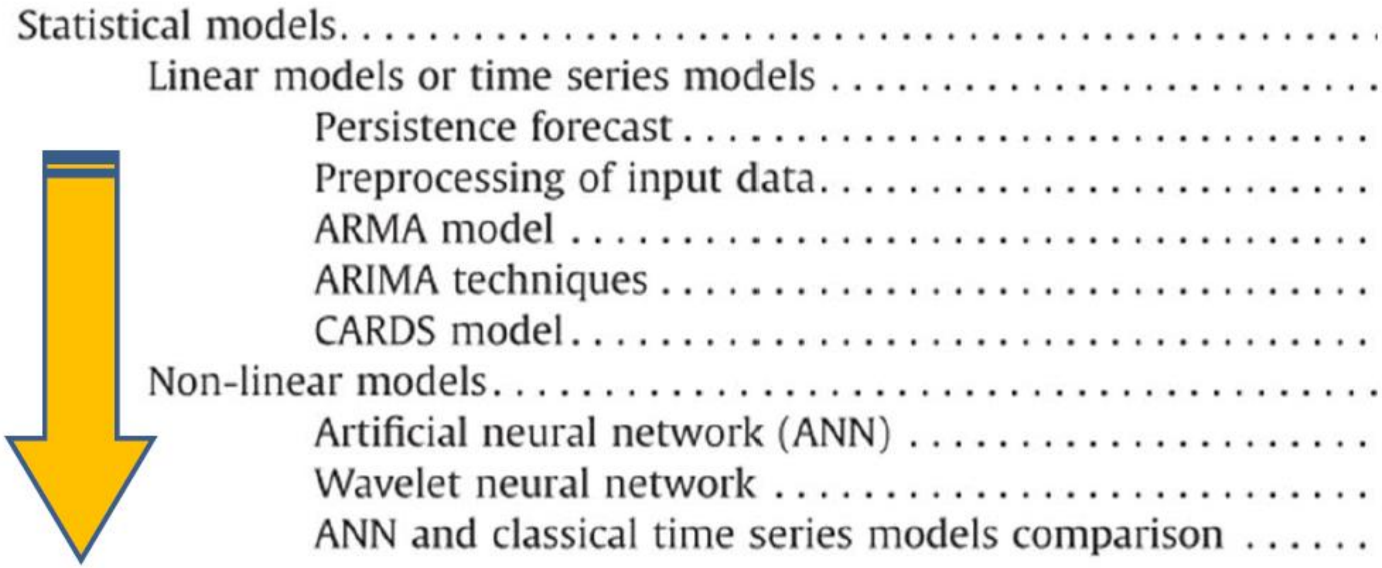
DNI forecast - how?

- Factors
  - Sun
  - Clouds
  - Aerosols (dust…)
  - Water vapor

- Techniques
  - Statistical
  - Numerical weather predication model NWPM
  - Satellite
  - Sky cameras



DNI Forecast
statistical



- Statistical models. . . . .
  - Linear models or time series models . . . .
    - Persistence forecast . . . .
    - Preprocessing of input data. . . . .
    - ARMA model . . . .
    - ARIMA techniques . . . .
    - CARDS model. . . . .
  - Non-linear models. . . . .
    - Artificial neural network (ANN) . . . .
    - Wavelet neural network . . . .
    - ANN and classical time series models comparison . . . . . .

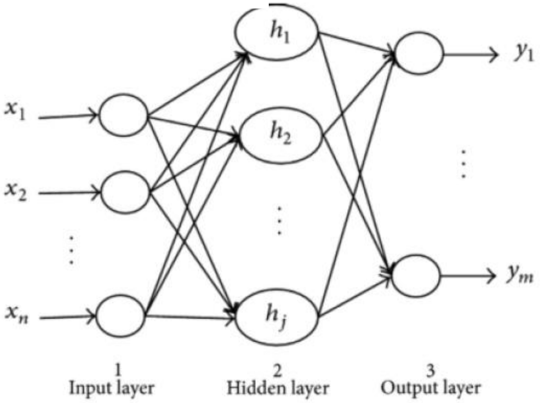
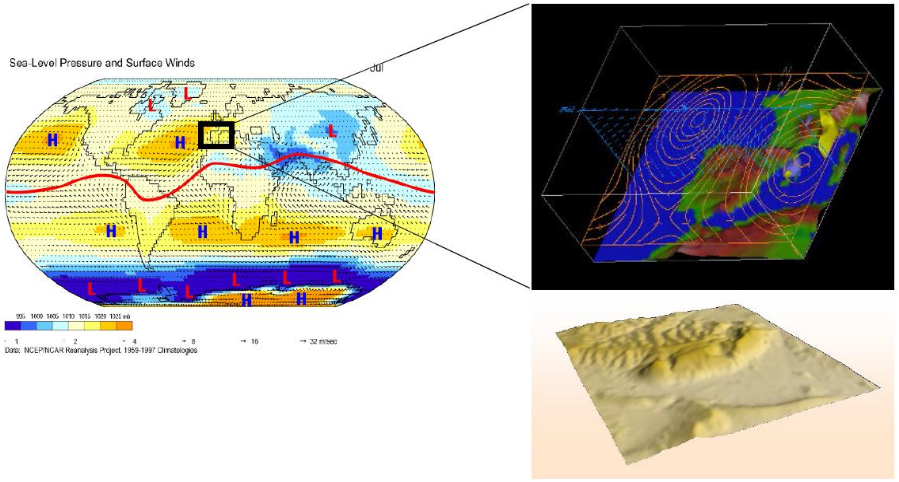


Fig. 2. Topology of wavelet neural network. Extracted from Gaige [30].

DNI Forecast
Numerical weather model

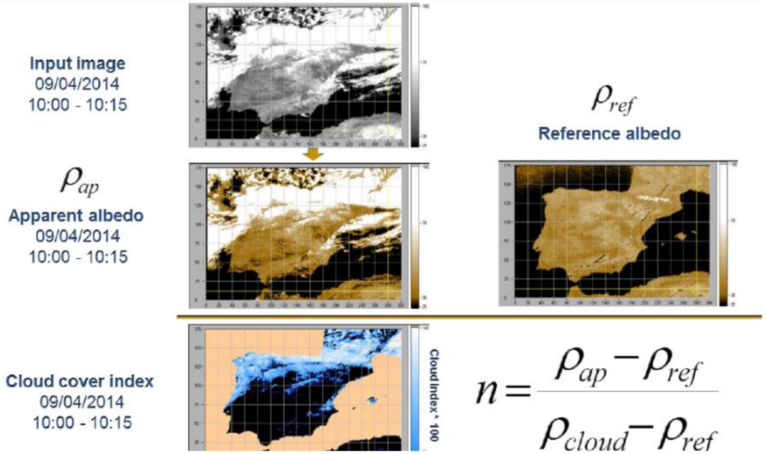
- Weather forecast
- Initial conditions input
- Different equations describing the evolution of the atmosphere are resolved
- PLUS ground measurements for
  - Assimilated in the model
  - Post-processing treatment



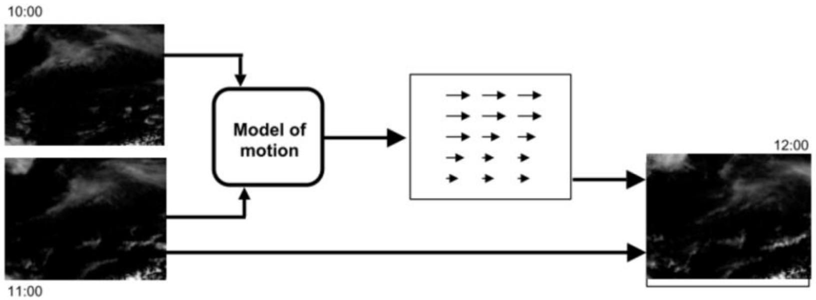
DNI forecast

Satellite-derived models

- detectors are placed at geostationary satellite
- faced to the earth surface,
- seen an Earth part typically of 60 degrees around the sub-satellite point
- with a resolution in a range from 1 up to 10 km.
- Satellite images time frequency use to be between 15-30 minutes.

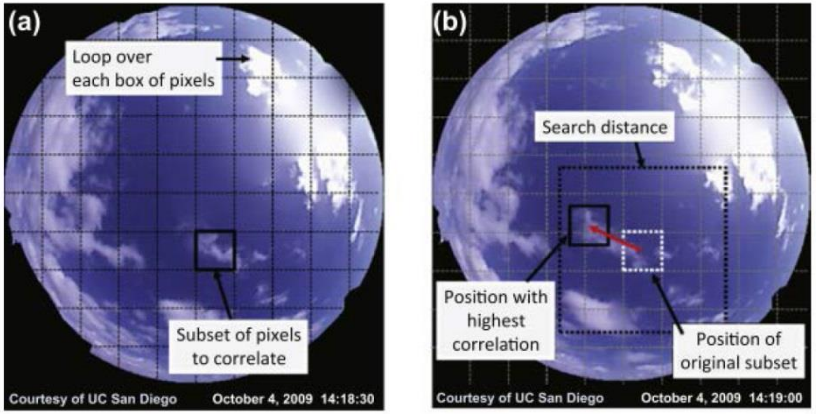


$$n = \frac{\rho_{ap} - \rho_{ref}}{\rho_{cloud} - \rho_{ref}}$$



DNI forecast
Derived from sky-camera images

- detectors are placed at ground level faced to the sky,
- seen the sky equivalent to 2 km around the camera locations
- with a resolution between 1-10 m per grid point.
- Sky images time frequency use to be configured between 1-60 seconds.



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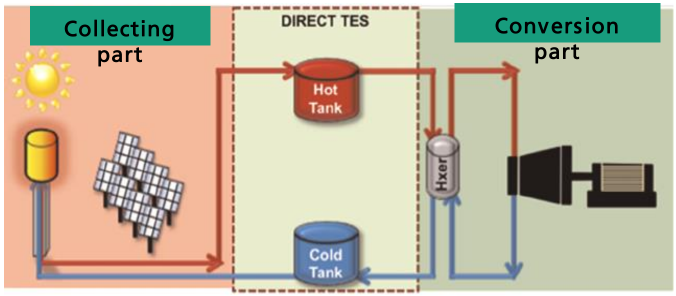
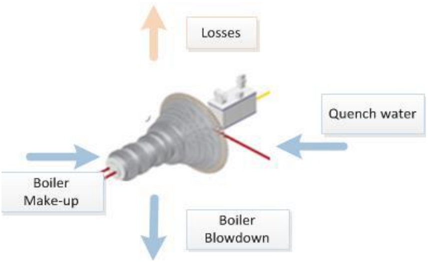



Planta solar Gemasolar propiedad de Torresol Energy ©SENER

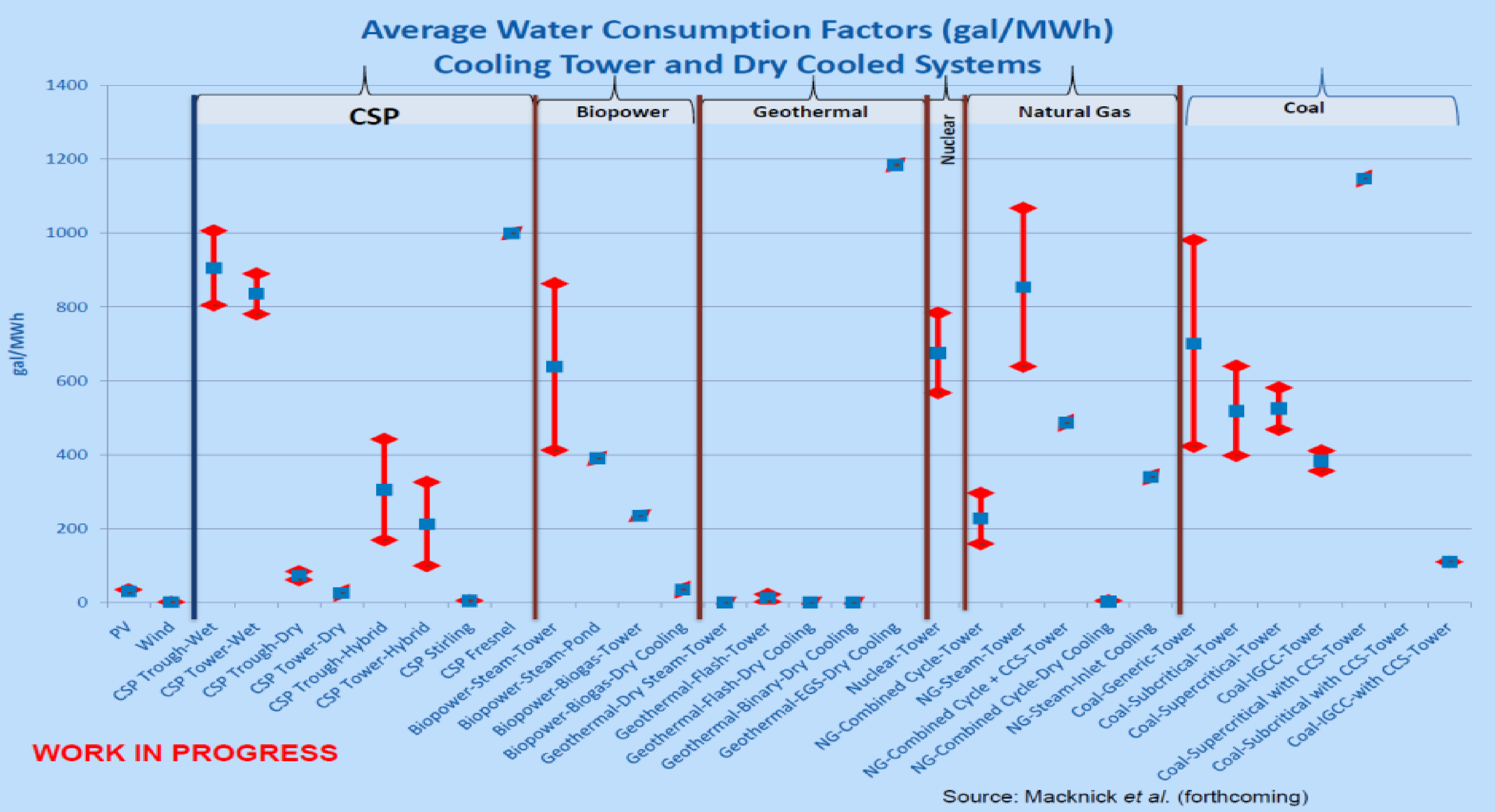
WATER CONSUMERS IN CSP PLANTS

- **Four main water consumers:**
  - Cooling system
  - Mirror cleaning
  - Steam cycle
  - Miscellaneous (e.g. bundle cleaning , filter backwash, auxiliary machine cooling, flocculent hydration, ozone generator cooling, centrifugal cleaning etc.)



WATER USE IN CSP PLANTS

- CSP plants use water in various qualities and quantities just as other thermal power plants.

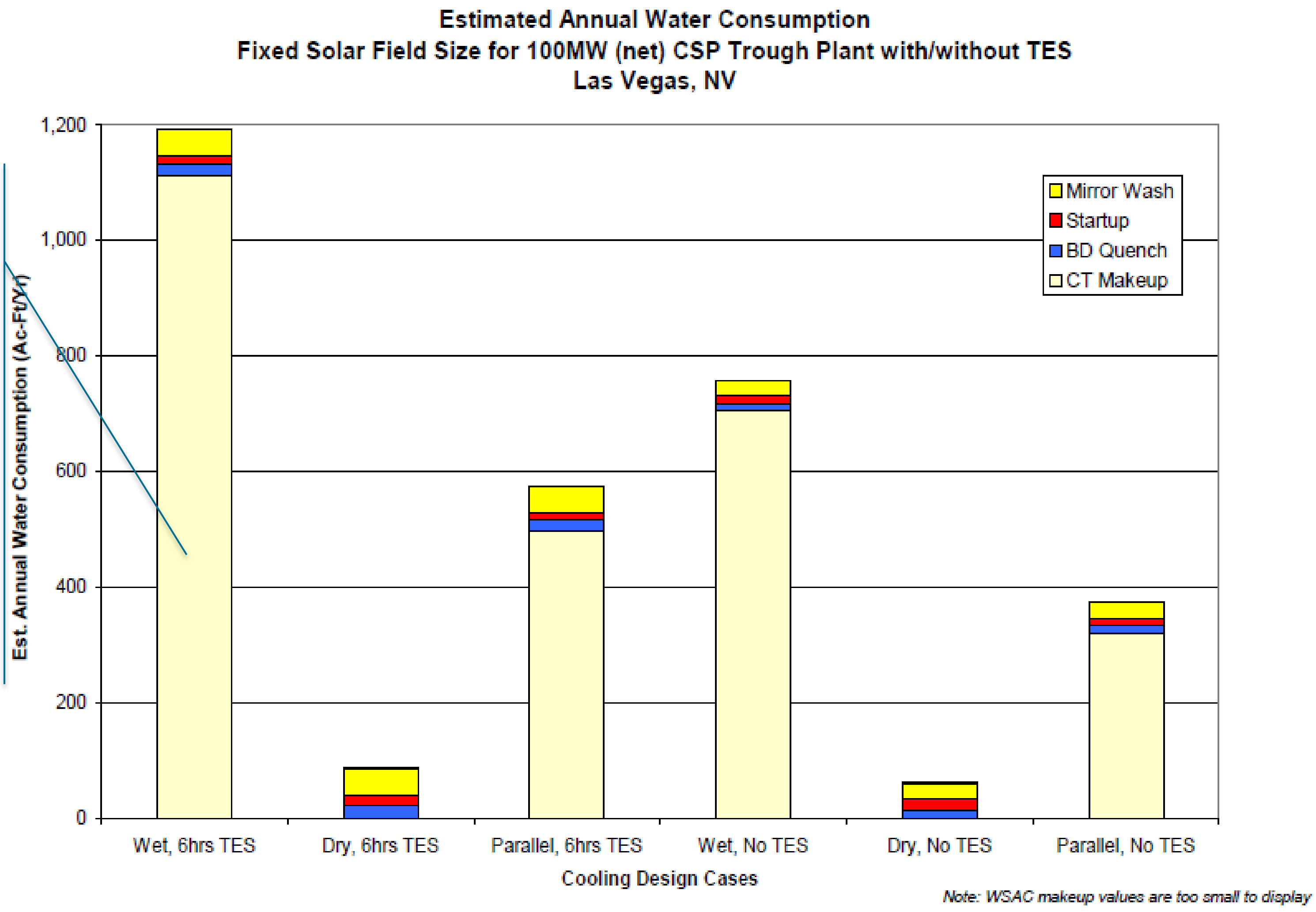


WORK IN PROGRESS

Source: Macknick *et al.* (forthcoming)

WATER CONSUMPTION, AN OVERVIEW

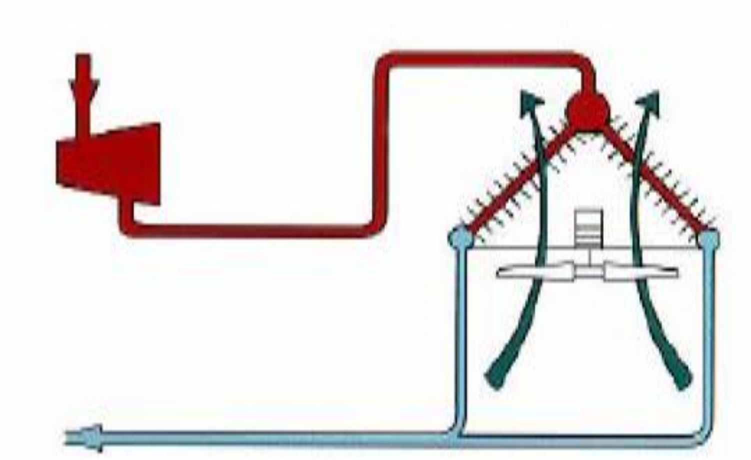
~93% of the wet condensing plant's annual water consumption is used by the evaporative cooling tower.



Note: WSAC makeup values are too small to display

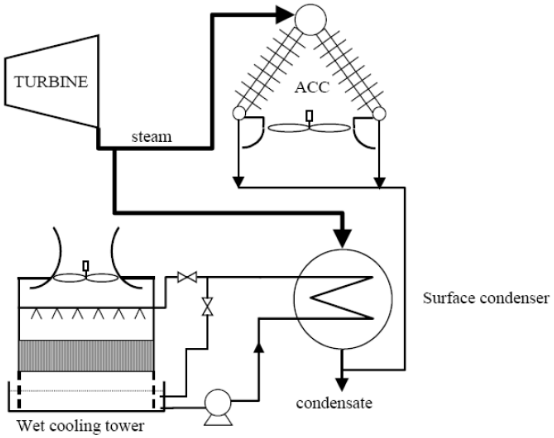
AIR-COOLED CONDENSER

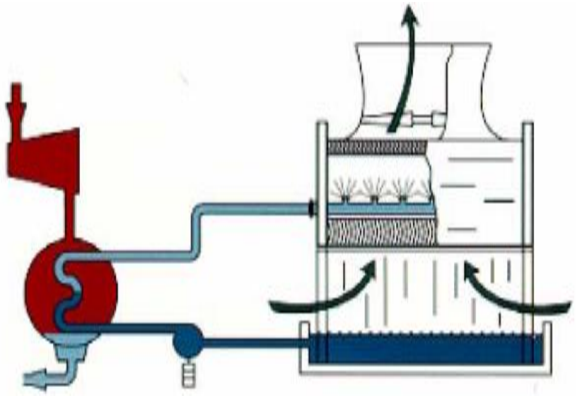
- **No water** consumption for cooling
- Higher turbine backpressure due to dry bulb ambient temperature -> lower energy conversion efficiency
- High installation cost
- Higher parasitics due to energy consumption of the cooling fans
- **2.5 to 9% increase in LCOE** depending on climate



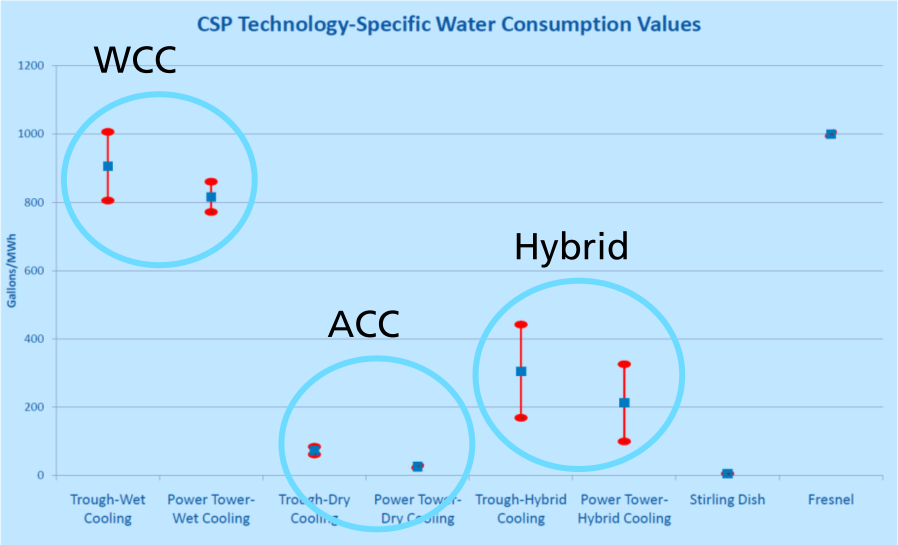
WET-COOLED CONDENSER AND HYBRID COOLING

- WCC
  - Approx. **13 times higher water consumption** compared to plants with ACC
  - Higher energy conversion efficiency -> **lower LCOE**
  - Lower installation cost
- Hybrid dry/wet
  - Water consumption decreased by 30 to 85%
  - Annual electrical yield reduced by 1 to 5%

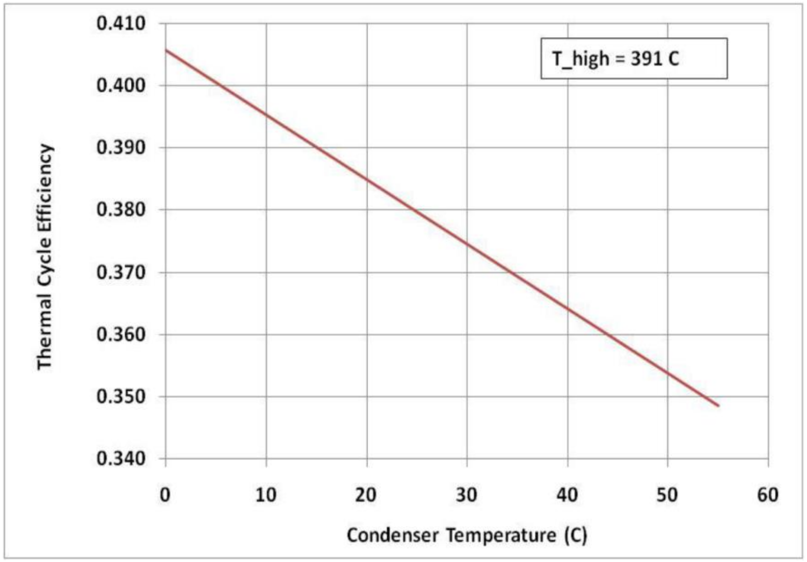




ACC VS. WCC AND HYBRID COOLING



Source: Macknick *et al.*, forthcoming

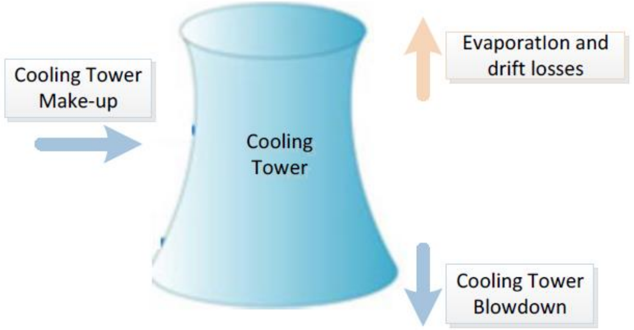


Current status:

- **more than 67%** of world installed CSP capacity is **equipped with WCC** (62 plants, including all operating Spanish plants except Puerto Errado 2)
- Only **one hybrid** CSP plant (110 MWe), Crescent Dunes, USA
- No CSP Plant with sea water cooling yet (maybe Akarit CSP Plant Tunisia)

WATER DEMAND OF THE COOLING SYSTEM

- Increase in salt concentration due to losses
  - **evaporation**
  - **drift of fog droplets**
- **blow-down loss**: to limit the concentration
- Make-up water: to compensate the above losses



	Wet cooling tower	Hybrid	dry	Once through
Specific water demand [$\mathrm{m^3/MW_{el}hr}$]	2	0.5	0	86

Surface water / fresh water

Seawater!

WATER QUALITY REQUIREMENT FOR COOLING SYSTEM

Some of the important required parameters of the process water for cooling include:

- The concentration (total dissolved solids – TDS) in the blowdown should not exceed 600 to 900 ppm to avoid scaling on the heat exchanger surfaces. (VDI e. V. 2010)
- Conductivity: <220 mS/m
- Alkaline Earth (Ca^{+2}, Mg^{2+}): <11 mmol/l
- Total Hardness: 60-80 °d
- PH value at 20 °C: 7.5-8.52

➢ WCC: Water Treatment Unit is Part of CSP Plant

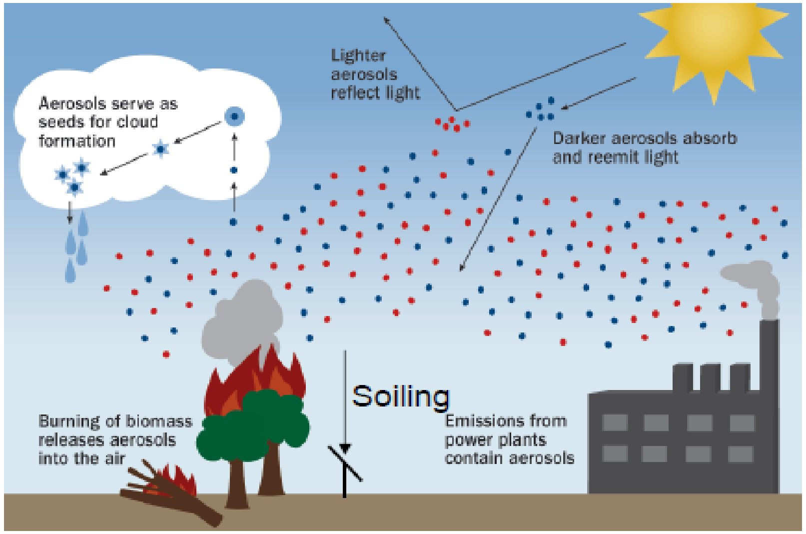
SOILING IN CSP PLANTS

- Power losses of 1% to 25 % per week in CSP due to soiling

↓

cleaning with water for high reflectivity of mirrors

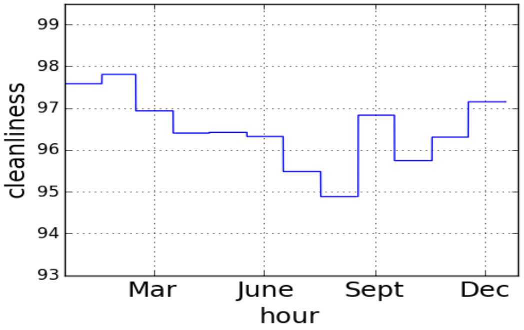
(in desert areas more frequently because of dust storms)



MEASUREMENT OF SOILING/CLEANLINESS

Objectives

- Monitoring the reflectivity of the mirrors to maintain the performance of the solar field
- Determining the most effective cleaning method based on the state of the field
- Detailed evaluation of impact of soiling and cleaning on the collectors
- Optimized mirror cleaning schedules for optimal utilization of water



Example for measured monthly mean cleanliness of a solar field

CLEANING CONCEPT PARABOLIC TROUGH COLLECTOR / HELIOSTATS

Truck based cleaning

- Contactless cleaning concept with water jet and / or high pressure air, which performs a function, first descaling and second sweeping or hosing for soil removal
- High speed, no surface contact

Contact cleaning with brushes (usually as a complement to the prior technic)

- PRO: Lower water consumption, high efficiency
- CON: If dust contains hard minerals / salts, this technique can scratch the mirror surface, reducing its reflectivity irreversibly.

CLEANING CONCEPT LINEAR FRESNEL COLLECTOR

Robot based cleaning

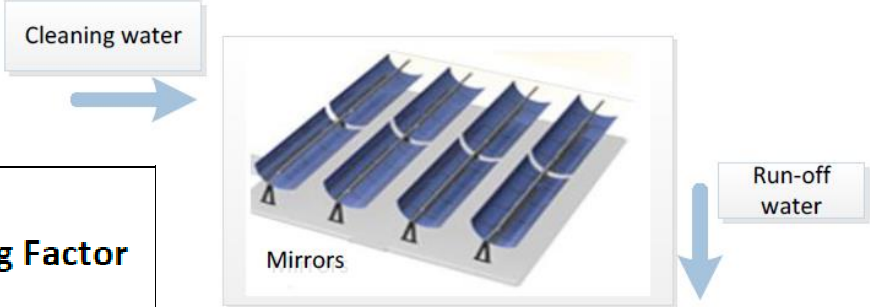
- Cleaning robot for Linear Fresnel primary mirrors
- System for cleaning the secondary mirror and receiver tubes
- ➢ Automated
- ➢ Low water consumption
- ➢ Automated reflectivity measurement

WATER DEMAND OF THE MIRROR CLEANING SYSTEM

- Contact method consumes less water, it is considered slower, but in turn produce a better result
- The water consumption average depends on the type and amount of soil presented on the mirrors
- **Average cleaning cycle is 1-2 weeks** depending on the site, characteristics of the dust, cleaning technology etc.

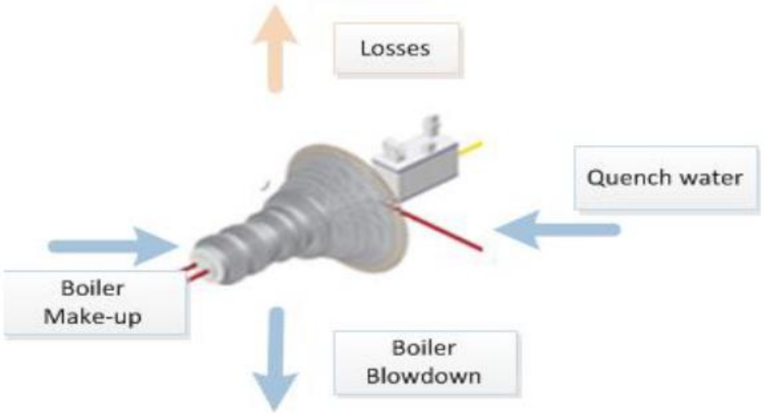
Example measured mirror washing water consumption and cleanliness:

Cleaning method	Water Consumption [l/m²]		Cleaning Factor
	Heliostats	PT	
Water jet	0,85	0,75	95%
brushes	0,8	0,7	99%



WATER DEMAND OF THE STEAM CYCLE

- **Losses** in steam cycle:
  - **flashing** of steam generators to maintain a specific condensate quality
  - **spillages** during startup
  - constant **blowdown** of vessels to maintain the condensate quality etc.
  - **quench** water
- These losses must be recovered with demineralized water for the boiler. Conventionally, the steam cycle consumes about **0.04 – 0.07 m^3/MWh** of make-up water.



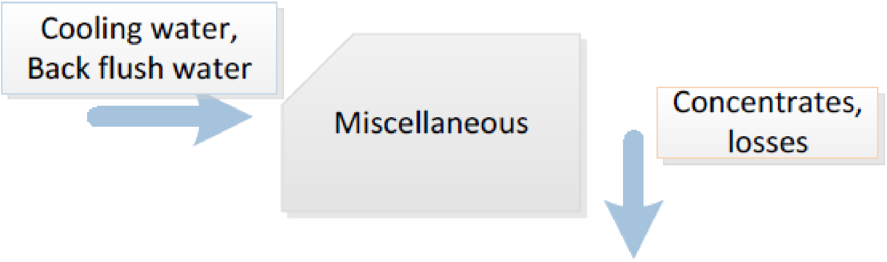
WATER QUALITY REQUIREMENT FOR STEAM CYCLE

- To avoid **fouling** or **scaling** of the steam turbine, the supplied water has to be demineralized at a **salinity** of 0.001 g/l (Doll, Venkatadri 2013). While mirror cleaning has low requirements with regard to the softening, for the demineralized water the high quality requirements make necessary at least a **reverse osmosis** treatment and in many cases additional **electrodeionisation** or **ion exchange** process stages.
- The total **organic carbon** should be very low (TOC < 0.05 mg/L). The organic components can cause **hydrothermolyses**. In this process organic acids can be produced which can intensify **corrosion**.

MISCELLANEOUS WATER DEMAND

- Another class of feed water consumers within the water treatment process can also be termed miscellaneous activities. These activities often involve filter backwash, bundle cleaning, auxiliary machine cooling, flocculent hydration, ozone generator cooling, centrifugal cleaning etc. (Gude 2015).

- To account for the aforementioned miscellaneous activities, the water requirement is calculated to be around **0.007 m³/MWh**.

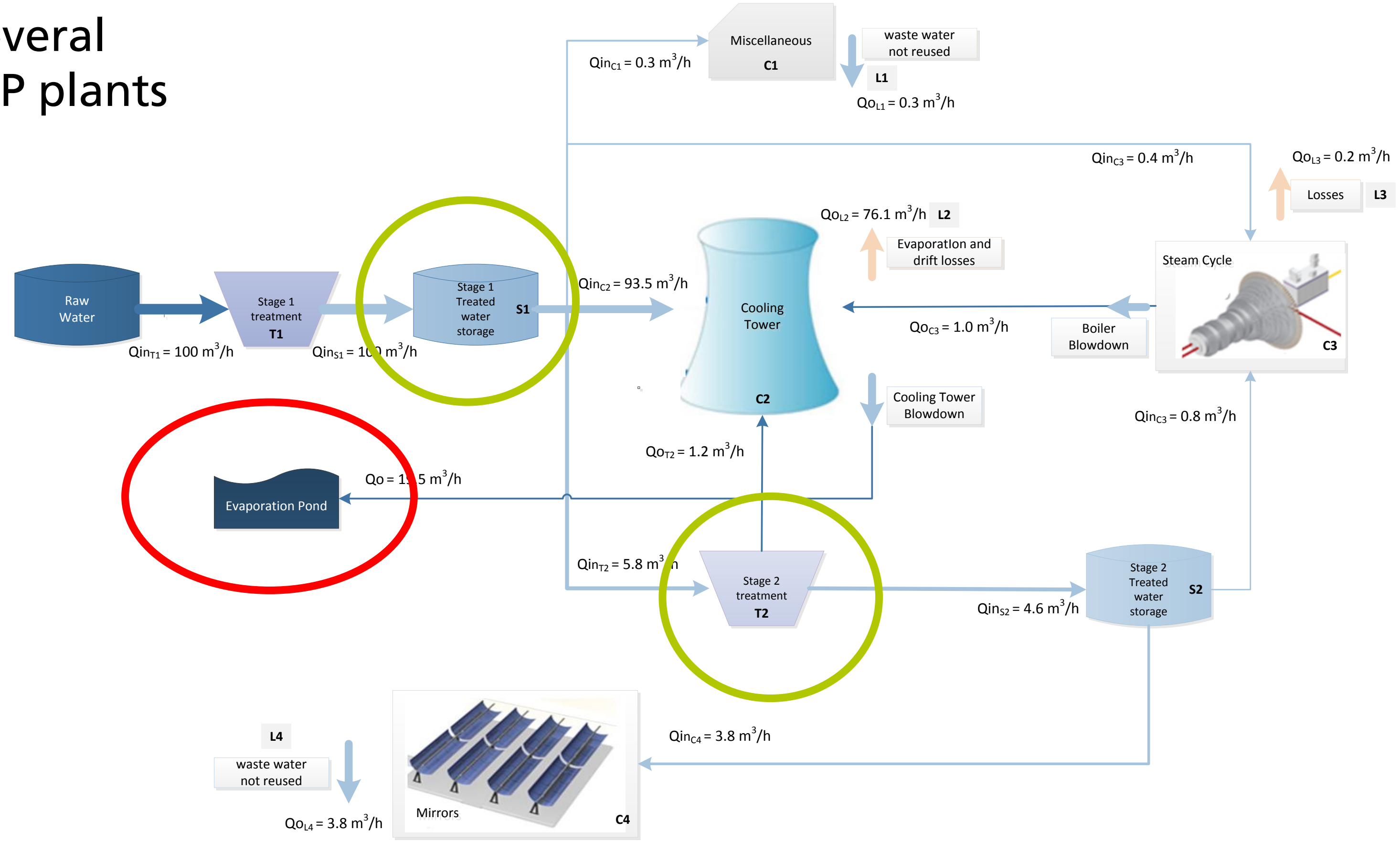


HANDLING OF EFFLUENTS AND WASTEWATER

- Each treatment step produces effluents in the form of **concentrates**, **backwash** water or **discharge** from cleaning or regeneration processes.
- Even the water consumers produce reject or **wastewater**.
- These effluents have to be handled within the **water management** system of the plant. They can be discharged in water receiving bodies or disposed. For the discharge of effluents, international and local regulations have to be taken into account.

WATER MANAGEMENT PLAN

Based on several
realized CSP plants



Miscellaneous **C1**

$Qin_{C1} = 0.3\ m^3/h$

waste water not reused **L1**

$Qo_{L1} = 0.3\ m^3/h$

$Qin_{C3} = 0.4\ m^3/h$

$Qo_{L3} = 0.2\ m^3/h$

Losses **L3**

$Qo_{L2} = 76.1\ m^3/h$ **L2**

Evaporation and drift losses

Steam Cycle **C3**

Raw Water

Stage 1 treatment **T1**

Stage 1 Treated water storage **S1**

$Qin_{C2} = 93.5\ m^3/h$

Cooling Tower **C2**

$Qo_{C3} = 1.0\ m^3/h$

Boiler Blowdown

$Qin_{T1} = 100\ m^3/h$

$Qin_{S1} = 100\ m^3/h$

Cooling Tower Blowdown

$Qin_{C3} = 0.8\ m^3/h$

$Qo_{T2} = 1.2\ m^3/h$

Evaporation Pond

$Qo = 15.5\ m^3/h$

$Qin_{T2} = 5.8\ m^3/h$

Stage 2 treatment **T2**

Stage 2 Treated water storage **S2**

$Qin_{S2} = 4.6\ m^3/h$

L4

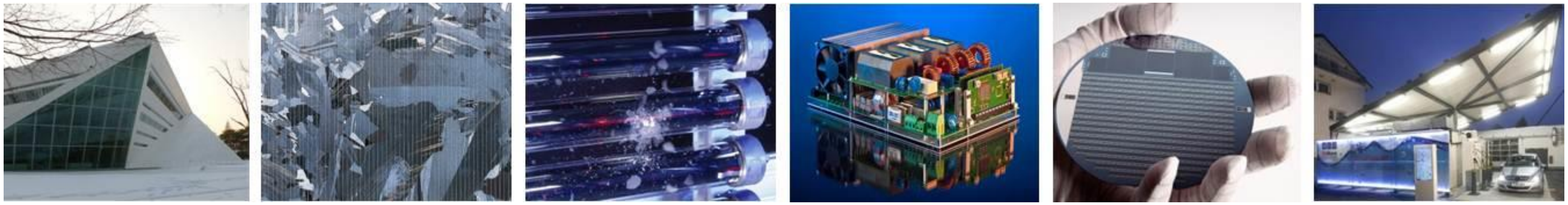
waste water not reused

$Qo_{L4} = 3.8\ m^3/h$

Mirrors **C4**

$Qin_{C4} = 3.8\ m^3/h$

Thank you for your attention!



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