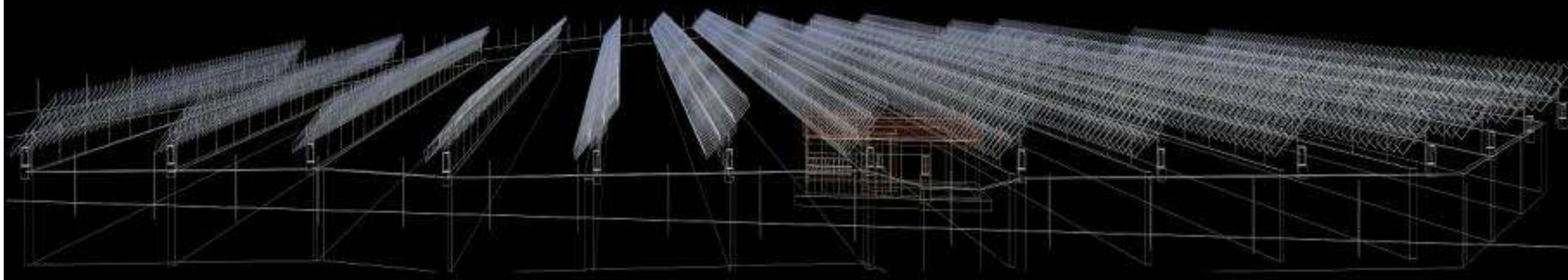


ABB Solar Center of Competence , IRES Workshop. December 16th 2011

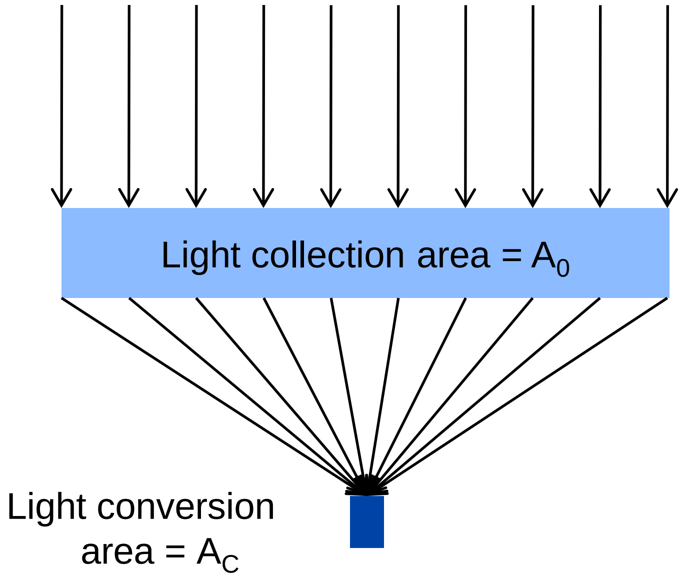
Solar Concentration Technologies
CPV Solar systems

The technologies
Concentrating PV

- Utilize high efficiency cell and reduce module cost by combination with low cost optical system
- Improvements could be fast since no semiconductor processing involved for module enhancements

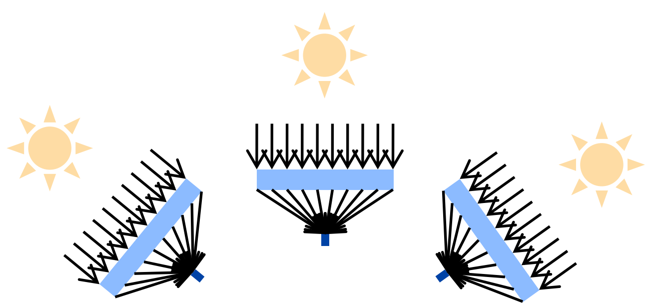
Source: Amonix, Concentrix, Greenvolts, SolFocus

CPV decouples the area used for light collection from the area used for light conversion into electricity



Sun concentration factor $C_F = \dfrac{A_0}{A_C}$

- Leverage cheap optics
- Leverage high-efficiency but expensive cells

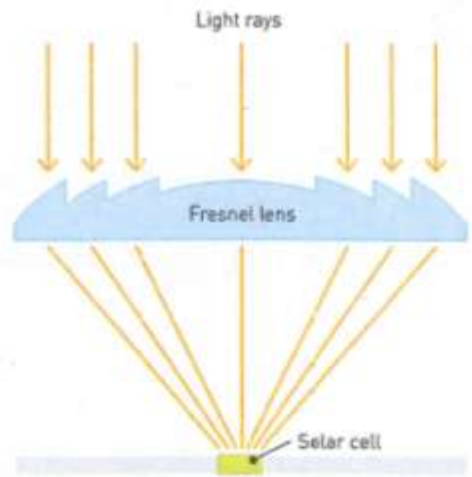


- The trade-off is that the higher the concentration factor, the more accurate the tracking system needs to be

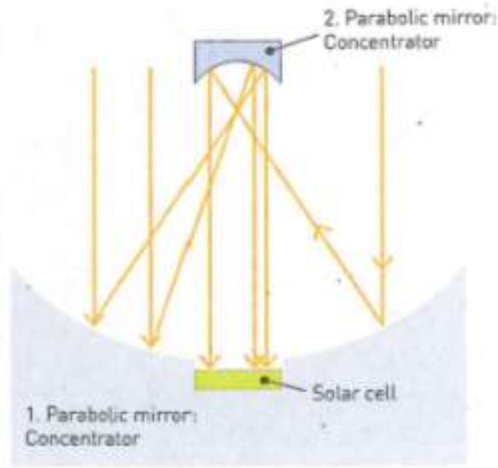
Overview of major CPV technology segments

High Concentration factor PV (HCPV)

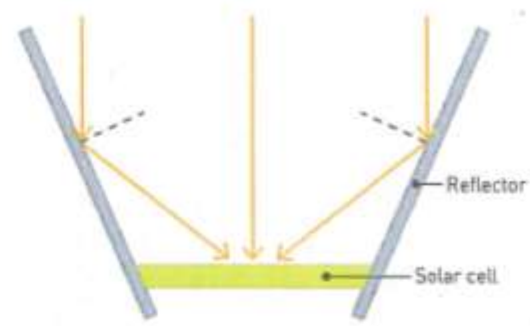
with Fresnel lens



with parabolic mirror



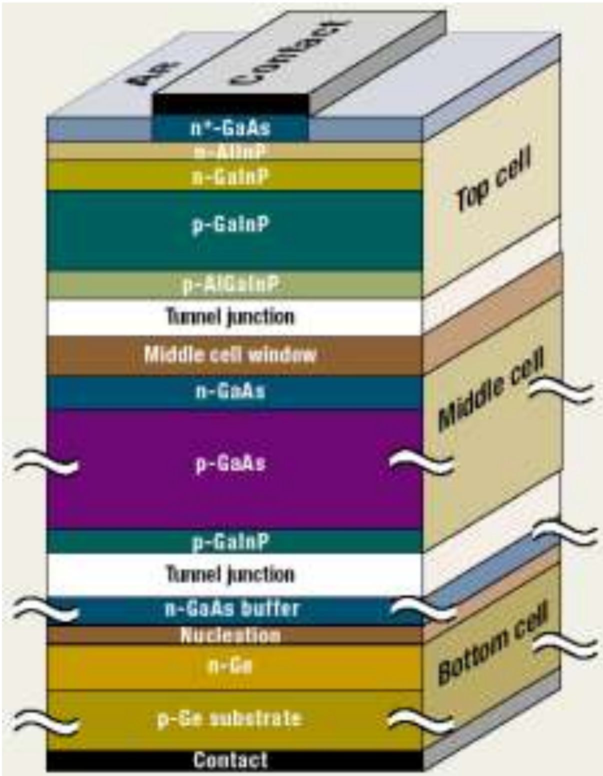
Low-concentration factor PV (LCPV) with simple reflectors



Other reflection arrangements are also used

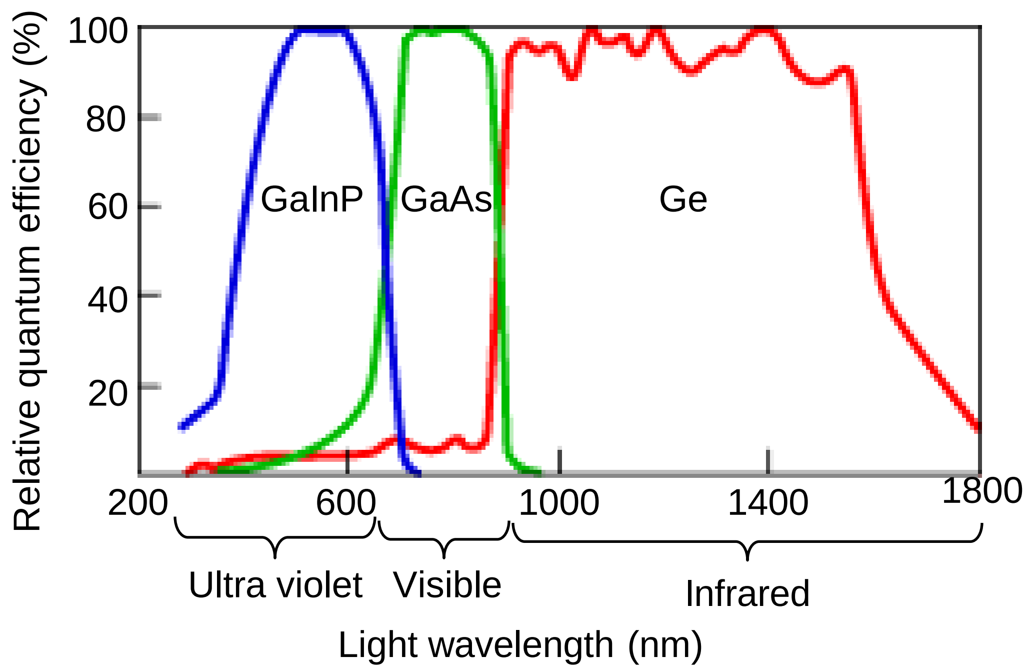
	High Concentration factor PV (HCPV)	Low Concentration factor PV (LCPV)
Concentration factor	▪ 300 to 1000	▪ 2 to 50
Tracking	▪ Precise 2-axis	▪ Normally 1-axis
Cells	▪ High efficiency **III-V multi-junction** ▪ Cells available from more than 15 suppliers ▪ Cell efficiency ~40%	▪ Modified Si cells, normally used but other cells may be readily substituted ▪ Cell-efficiency ~20%
Sunlight conditions	▪ Direct solar insolation only	▪ Some use of diffuse / indirect insolation
Example companies	▪ Amonix, Concentrix, Greenvolts, SolFocus	▪ Skyline, Solaria, WS Energia

III-V triple-junction cells are a complex stack of ~20 different layers



Schematic of a III-V triple junction CPV solar cell

- III-V cells originally developed for space applications, where efficiency was much more important than cost
- Manufacturing technology very similar to that used fro LED & LASER structures: MOVPE (Metal Organic Vapor Phase Epitaxy)



- Each of the 3 cells in the III-V triple junction stack is tuned to absorb & efficiently produce electricity from a different part of the light spectrum
- The result is a cell that is significantly more efficient than any single junction cell

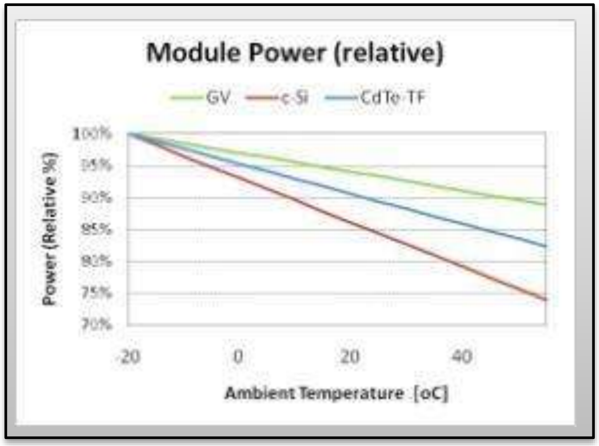
The CPV Technology Advantage

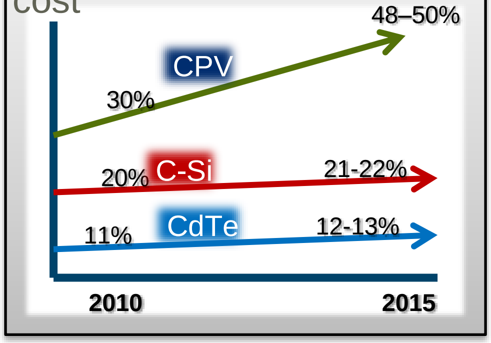
High Efficiency CPV Solutions have advantages over Thin Film and PV

Today
- CPV is more efficient than c-Si and CdTe
- CPV efficiency is even more superior in hot sunny regions
- CPV energy production increases with DNI

Future
- CPV is seeing enormous efficiency gains
- Thin film is nearing the end of its efficiency gains

Cost
- Cost reduction is dramatically “accelerated” by CPV efficiency gains
- Only 1% increase in cell efficiency yields 3% decrease in system cost



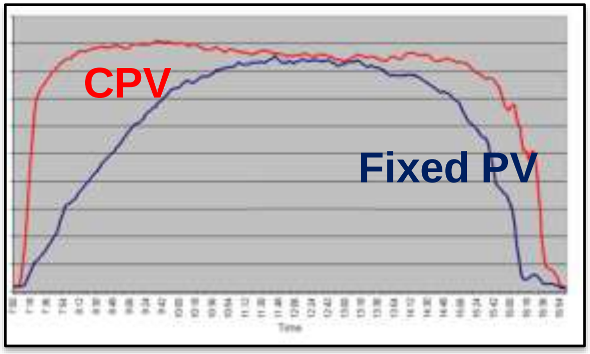


Efficiency vs. Time

Annual Energy Yield (MWh/yr)

Technology	1MW Plant Creates
CdTe Fixed	1,683 (100%)
c-Si 1 Axis	2,052 (122%)
CPV	2,397 (143%)

Higher Energy Production



Two-axis tracking maximizes harvesting of the solar resource over the entire day

Technologies comparison

Concentrator PV CPV

- Lowest LCOE potential
- Highest energy density
- Matches peak load demand
- Best in hot climates
- Readily scalable to GW
- Tracking Mandatory
- Requires Direct Sunlight

Photovoltaics (PV) Conventional Si

- Mature technology
- Indirect sunlight acceptable
- Tracking optional
- Efficiency approaching limits of technology
- Performance degrades at high temperatures

Thin Film

- Indirect sunlight acceptable
- Less temperature degradation than silicon PV
- Suited to rooftops/ construction
- Lowest Efficiency

Concentrated Solar Power CSP

- Cost effective in large installations
- Mature solar technology
- Significant water usage for cleaning and cycle
- Requires large deployments for cost efficiency

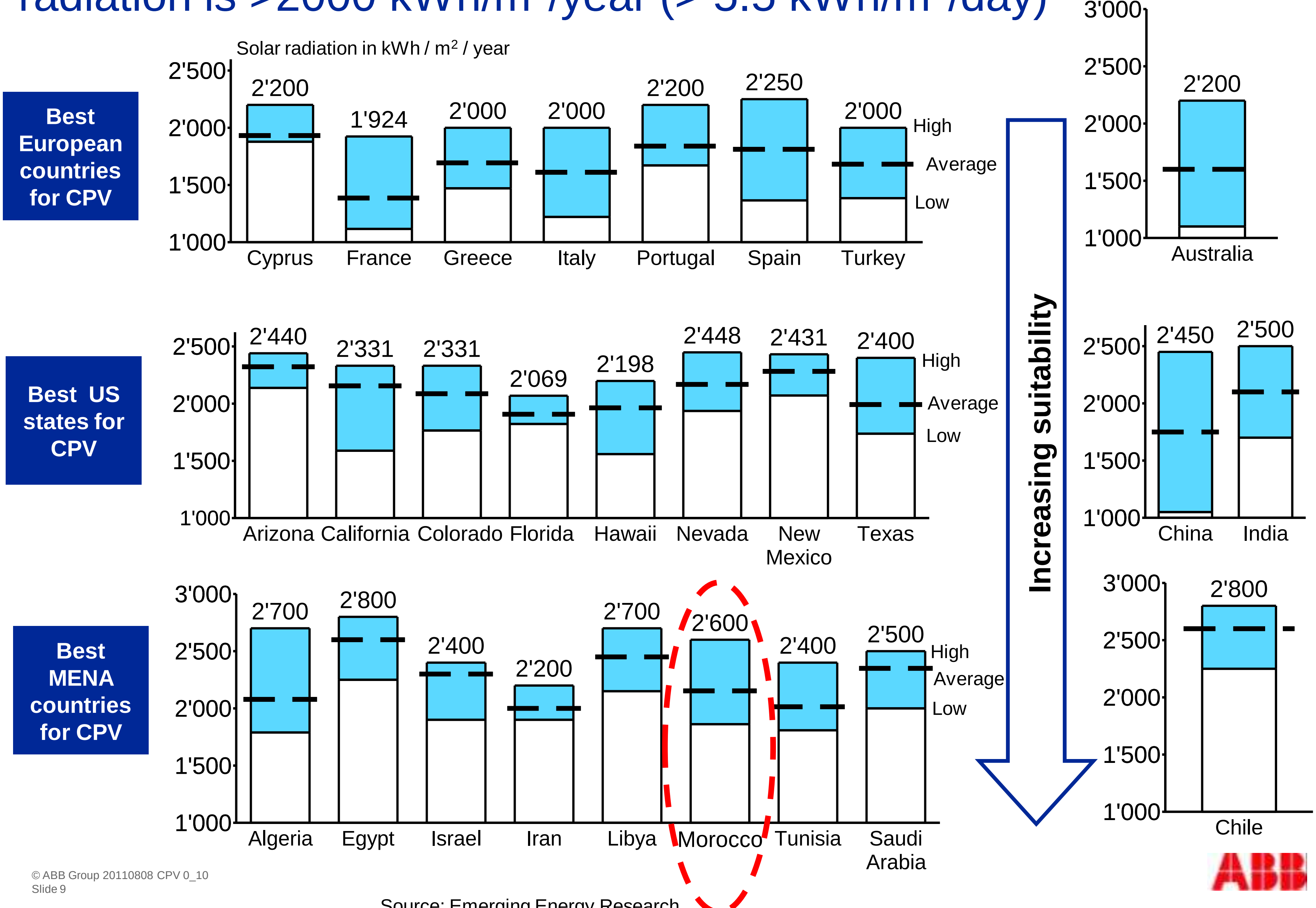
CPV and CSP are both best suited to utility scale applications in high DNI locations

	Standard PV	Concentrated PV	CSP (solar thermal)
Performance low DNI locations Ability to use diffuse i.e. non-direct sunlight	▪ Can use diffuse sunlight	▪ LCPV can use diffuse sunlight, HCPV cannot	▪ Cannot use diffuse sunlight
Performance in high DNI locations	▪ Large efficiency drop-off under high ambient temperatures	▪ DNI* should be >2000 kWh / m^2 / year	▪ DNI* should be >2000 kWh / m^2 / year
Modularity How scalable is the technology?	▪ ~10 kW upwards	▪ ~1 MW upwards	▪ ~30 MW upwards
Construction time Ground breaking to grid conection	▪ < 1 year, depends on size	▪ < 1 year, depends on size	▪ ~2 years ▪ Turbine island is on critical path
Energy payback time Time to generate energy used in manufacturing	▪ ~2 years	▪ < 1 year	▪ ~3 years
Water use How much water is required per MWh	▪ Small amount of water for cleaning	▪ Small amount of water for cleaning	▪ Dry cooling much better than wet cooling ▪ Make-up water rquired for steam-water cycle
Dispatchability / intermittency Abilty to offer consistent power levels during daylight	▪ Output constantly varies with cloud cover / DNI ▪ Batteries could be used to smooth output	▪ Output constantly varies with cloud cover / DNI ▪ Batteries could be used to smooth output	▪ Thermal inertia of steam system smooths power output
Ability to add storage Abiltiy to keep generating power after daylight	▪ Batteries could be used but would add ~$0.06 per kWh	▪ Batteries could be used but would add ~$0.06 per kWh	▪ Molten salt thermal storage ▪ Does not increase LCOE
Ability to hybridize Ability to implement natural gas / biomass co-firing			▪ Other fuels can be used to create suplementary steam
Ability to provide co-generation Ability to provide electricity & heat		▪ Low grade heat may be collected via active cooling	▪ High grade steam generated

- CPV and CPV have separate and distinctive differentiating attributes
- In the absence of disruptive technology breakthroughs or strongly biased government policy both technologies are predicted to play a niche yet significant role in the future energy mix

*DNI = Direct Normal Irradiance

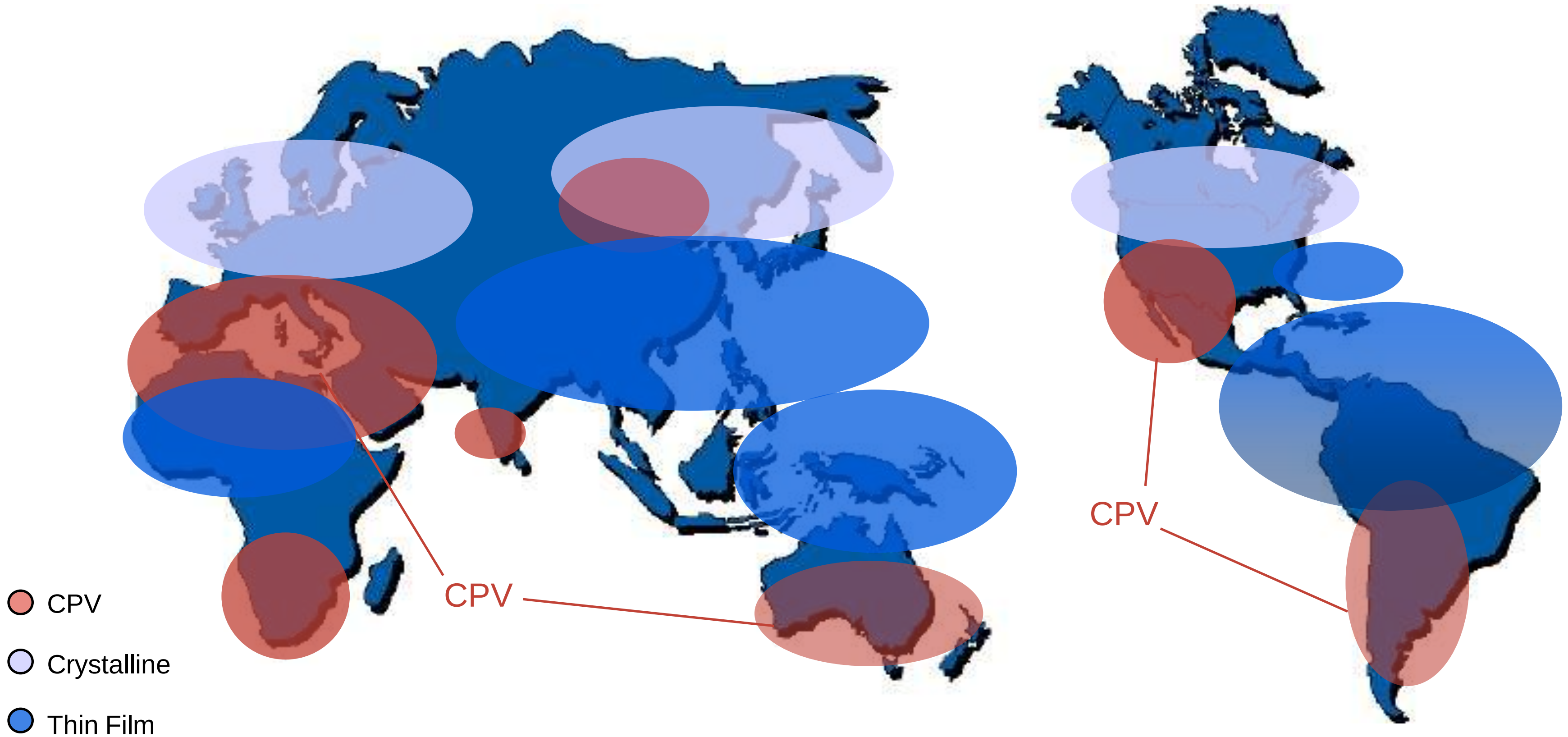
CPV plants are best suited to high DNI locations where solar radiation is >2000 kWh/m²/year (> 5.5 kWh/m²/day)



Source: Emerging Energy Research

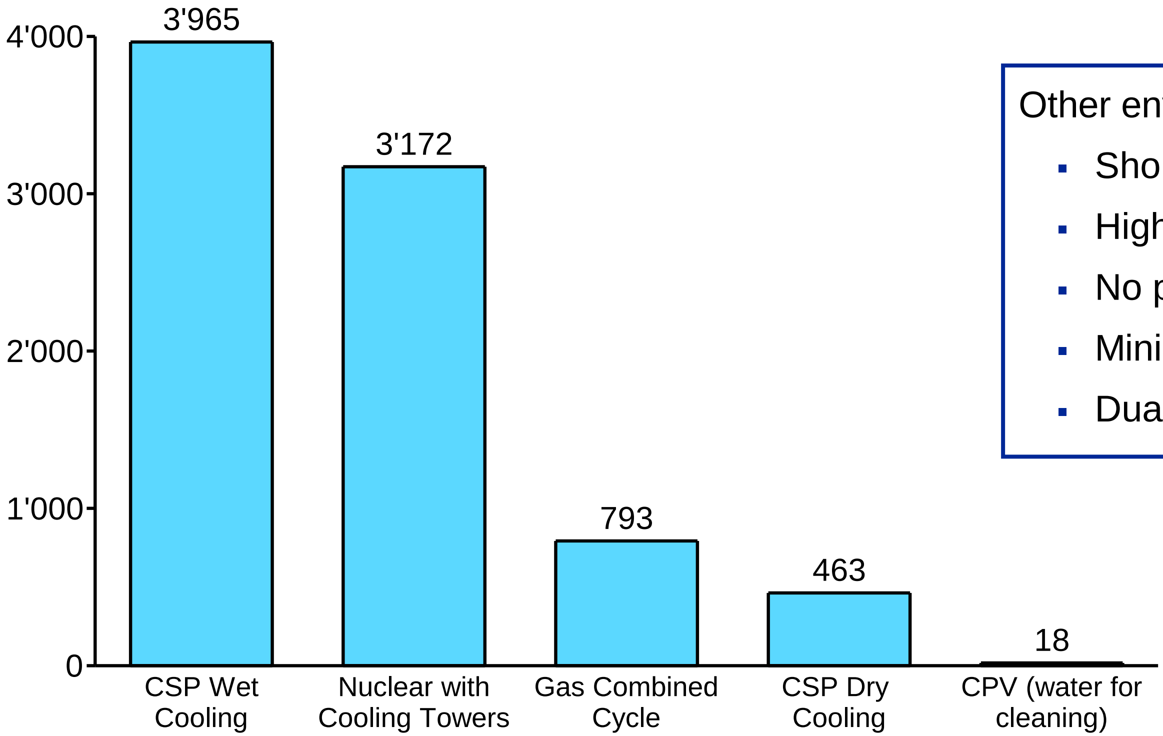
CPV Best in Sunny Regions

- Fastest Growing, Best-ROI Solar Markets
- ~35% of Land Area, 40% of Global Population



CPV plants use very little water, even compared to CSP plants with dry cooling

Comparison of water consumption liters per MWh



Other environmental benefits of CPV include:

- Short energy payback time
- High recyclability
- No permanent shading*
- Minimized erosion from water run-off*
- Dual use of land

* due to 2-axis tracking system panels are constantly moving during daylight hours

Four major arguments for (high)concentration PV:

CPV already cost competitive at high DNI

- In high DNI* locations (>2500 kWh/m^2/year) already cost competitive with standard PV
- Slim bill of materials, negligible dependence upon the price of silicon**
- Highest efficiency, efficiency improvements are ongoing at the rate of ~1% per year, improvement rate foreseen to continue

Great performance at high DNI

- III-V cells suffer little efficiency loss in hot environments
- CPV systems must use tracking, which leads to more output throughout the day
- ~30% more MWh per MW compared to non-tracked non-concentrated PV

Speedy & flexible implementation

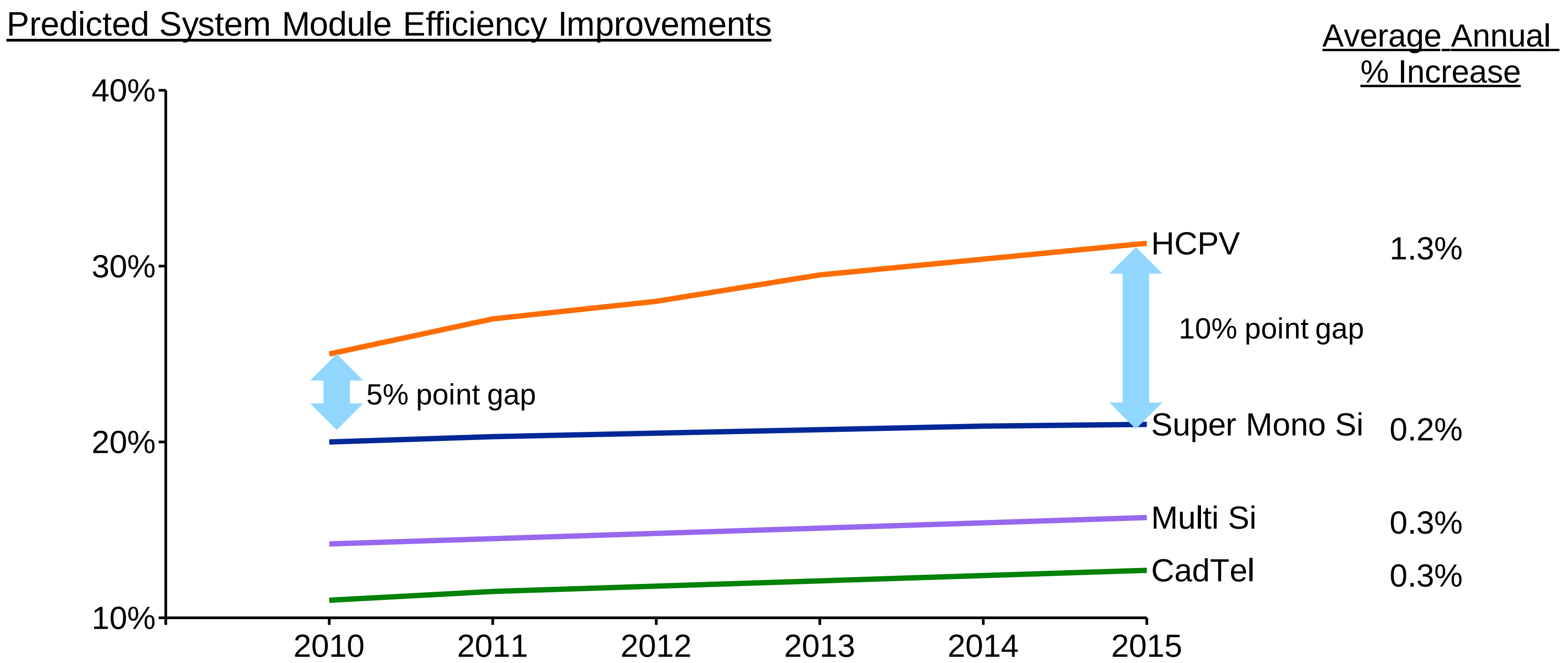
- 1 MW to 100 MW+
- Plants may be commissioned in phases
- No grading of land required for pedestal mounted systems (e.g. Amonix, SolFocus), some land grading required for systems from Greenvolts, Emcore

A very green renewable energy

- Very short energy payback time
- Negligible water required ~16 litters per MWh
- Local ecosystem is preserved, no permanent shading due to tracking movement of panels

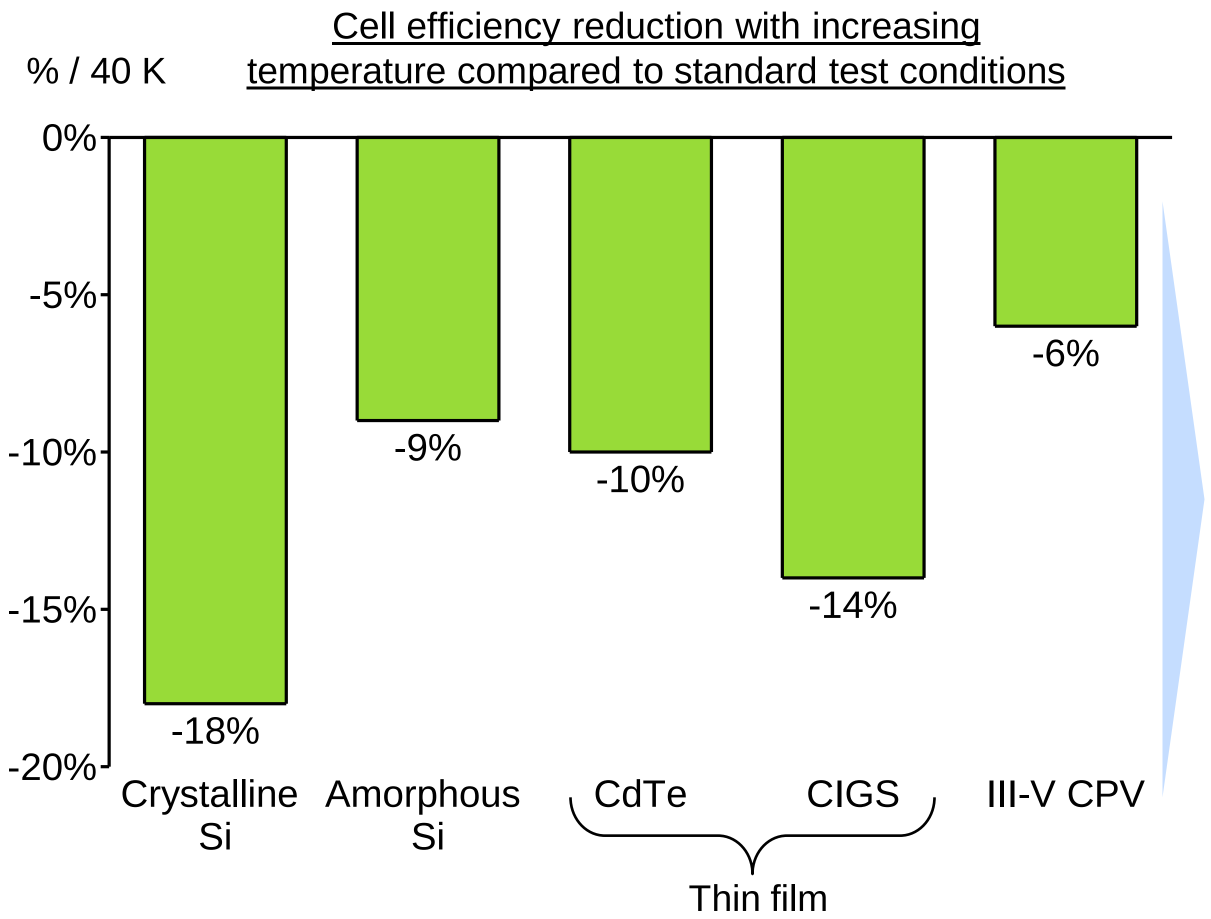
*DNI = Direct Normal Irradiance, ** Un & low concentrated PV costs are heavlily dependent upon the price of Silicon which is relatively voltatile , shortages of Silicon can lead to rapid increases in PV cell / module costs

High concentration module efficiency predicted to improve at a much higher rate compared to competing PV technologies



- System module efficiency improvements in-line with & driven by III-V cell efficiency improvements
- By 2015 HCPV modules predicted to be 10% points more efficient than the best mono Silicon modules
- Efficiency improvements are a key lever for reducing specific costs

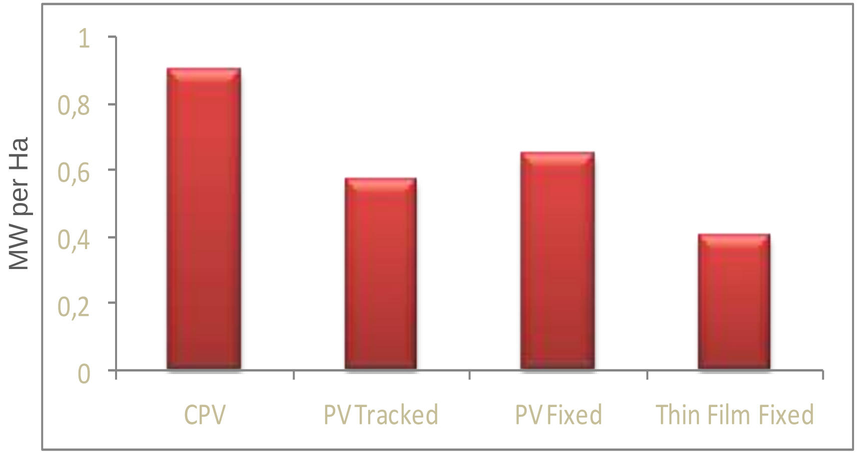
In locations with high ambient temperatures, III-V junction cells suffer much less of an efficiency loss than Si cells

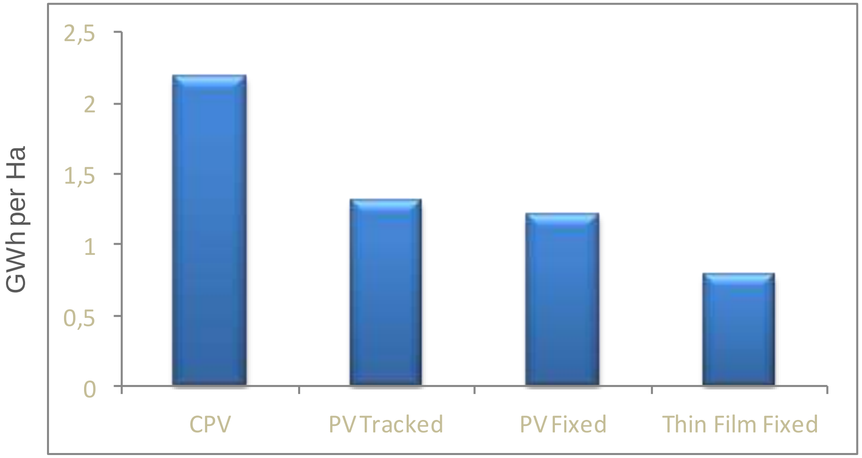


- Locations with high ambient temperatures correlate well with high DNI locations
- This phenomenon further improves the relative competitiveness of CPV in high DNI locations

Highest Power/Energy Density

- High Efficiency Panels Equals More Power per Site
- Enables Higher % of Load for Commercial Customers
- Better Use of Land
- Efficiency + Tracking = Higher Energy Efficiency





Calculating Levelized Cost of Electricity (LCOE)

$$\frac{\underset{\text{Installed System Cost}}{\$ / \text{Watt}_{DC}} + \underset{\text{25 years O\&M}}{\$ / \text{Watt}_{DC}} + \underset{\text{Finance Cost}}{\$ / \text{Watt}_{DC}}}{\underset{\text{Annual energy produced per peak-watt system rating}}{\text{kWh}_{AC} / \text{Watt}_{DC}}} = \underset{\text{LCOE}}{\$ / \text{kWh}_{AC}}$$

Watt_{DC} appears in both the nominator and the denominator of the above equation

- It is supposed to represent the peak DC power output of the system
- In reality the definition is somewhat arbitary
- To allow better comparison of $\$ / \text{Watt}_{DC}$ data standard test conditions have been derived
- Unfortunately the standard test conditions are not the same for standard PV & CPV

Comparison of standard nameplate test conditions	Ambient Temperature	Incident radiation
Non-concentrating PV & low concentration PV	20°C	1000 W / m^2
Mid & high concentration PV	25°C	850 W / m^2

ABB

Company Focus: Reduce LCOE

$$\text{Levelized Cost of Energy} = \frac{\text{NPV of Annual Cash Flows}}{\text{'NPV' of the Annual Energy Flows}}$$

lower

25Year Cost of Ownership

Equipment	Operations and Maintenance	Warranty

= $/KWh

better

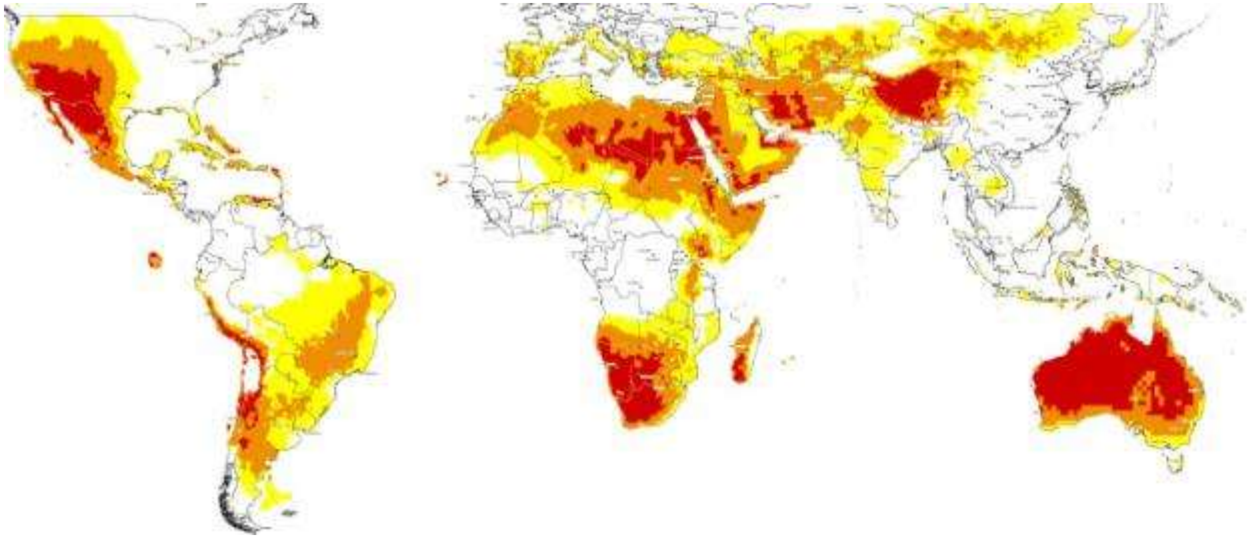
higher

25 Year Energy Output

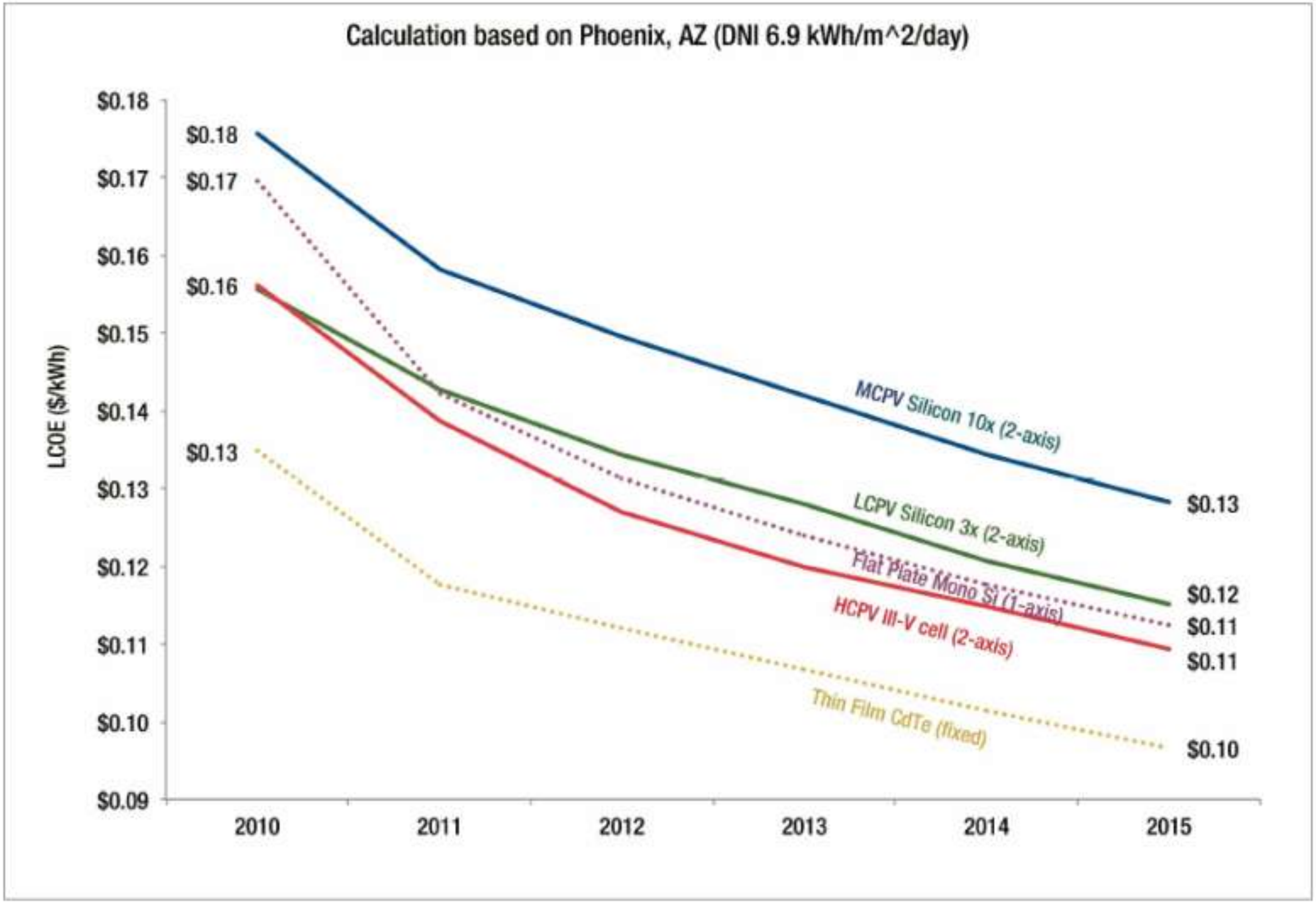
Efficiency	# Systems	Losses

Key Points

- An integrated solution will deliver the lowest LCOE
  - The opportunity for low LCOE can be achieved in med/high DNI areas
  - An integrated CPV solution is the only method to extract the full LCOE potential



LCOE– Different technologies



Source: GTM Research

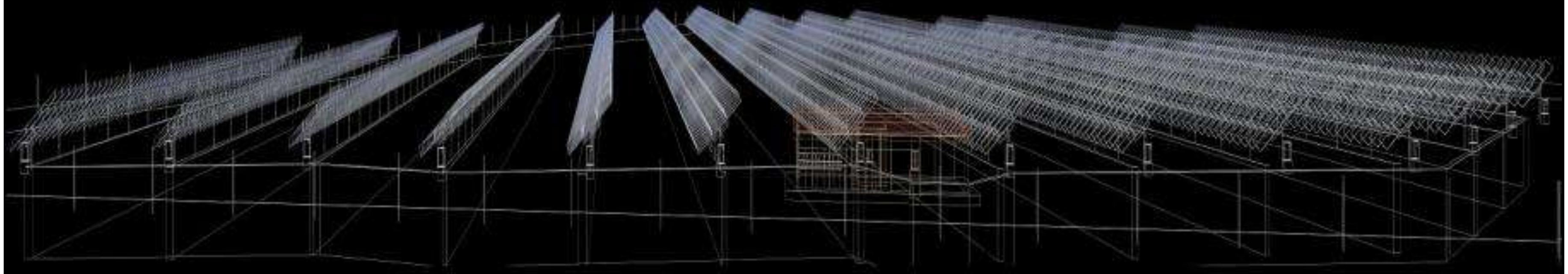


ABB Solar Center of Competence , IRES Workshop. December 16th 2011

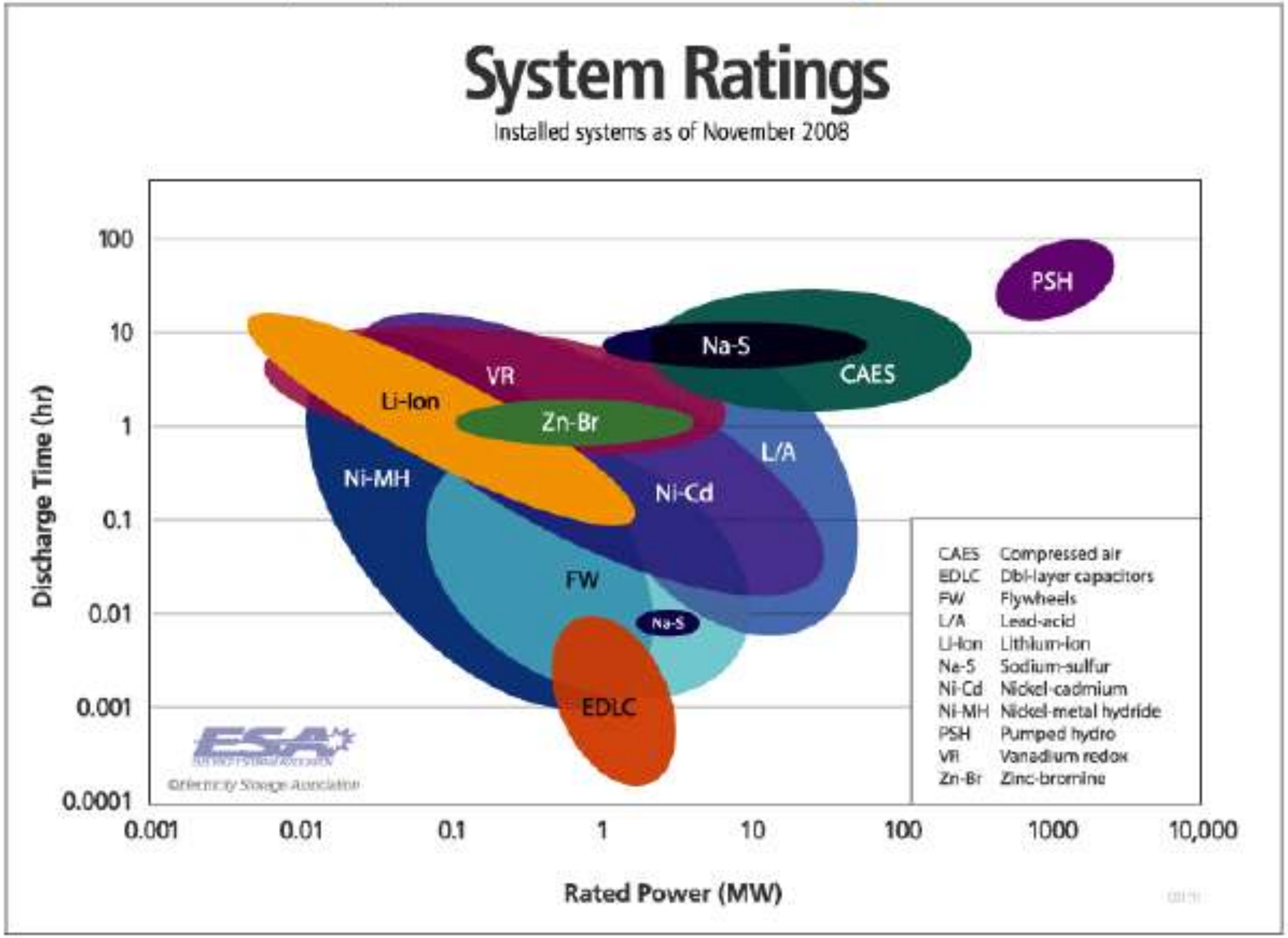
Energy storage for Solar systems
Technology survey

Energy Storage Technologies

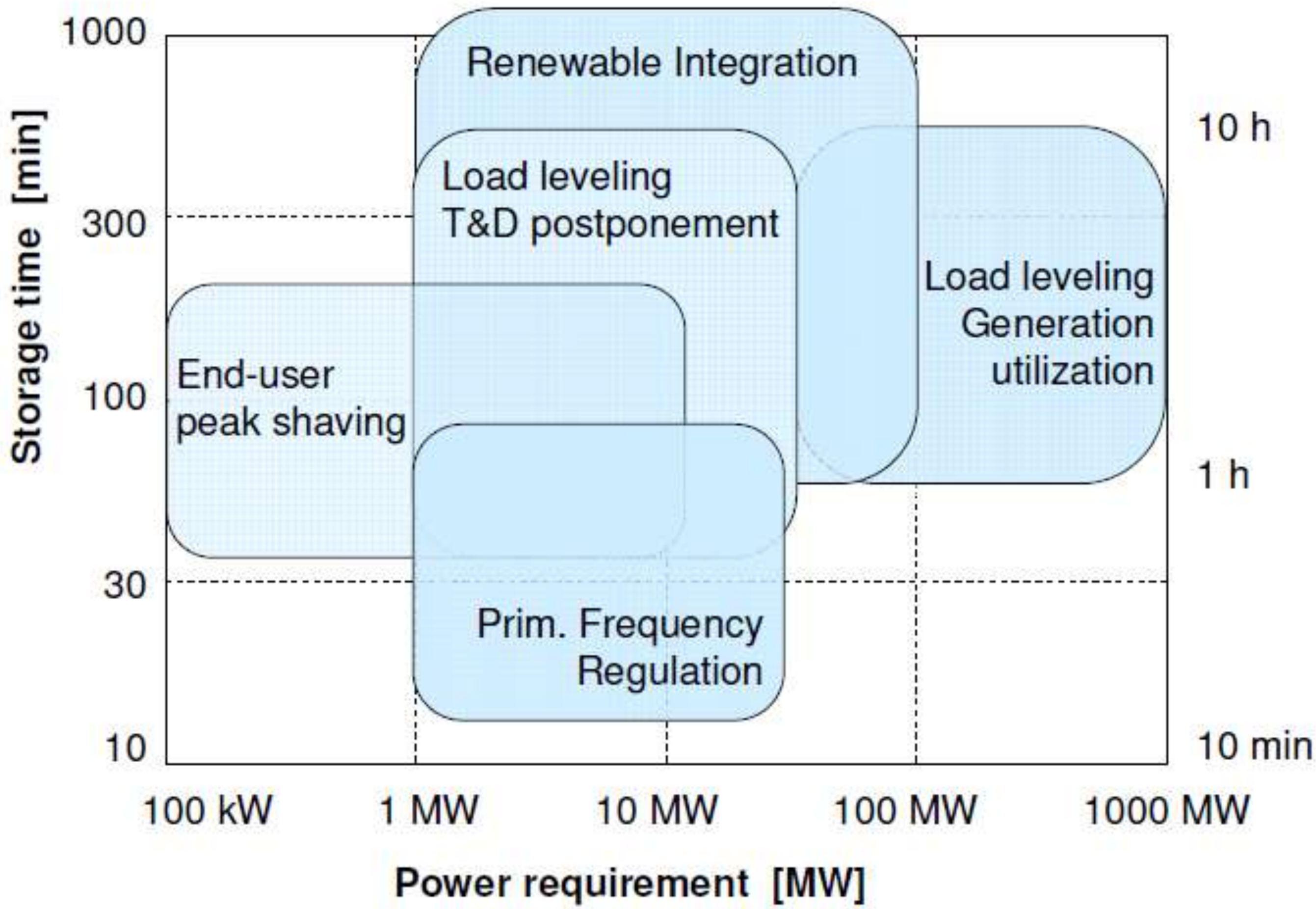
ENERGY

- **Mechanical**
  - Gravitation
    - Pumped hydro
  - Kinetic
    - Flywheel
- **Thermo-dynamic**
  - Heat
    - Molten salt
    - Thermo-electric
  - Pressure Heat
    - Compr. air (CAES) (A-CAES)
- **Electrochemical**
  - Batteries
    - Lead acid
    - NiCd
    - NaS
    - NaNiCl
    - Lithium
    - Ni-MH
    - Metal air
  - Flow cells
    - Vanadium
    - ZnBr
    - PSBr
  - Hydrogen
    - Electro-lyser & Fuel Cell
- **Electro-magnetic**
  - Electric
    - Capacitors
    - Supercaps
  - Magnetic
    - Super-conducting (SMES)

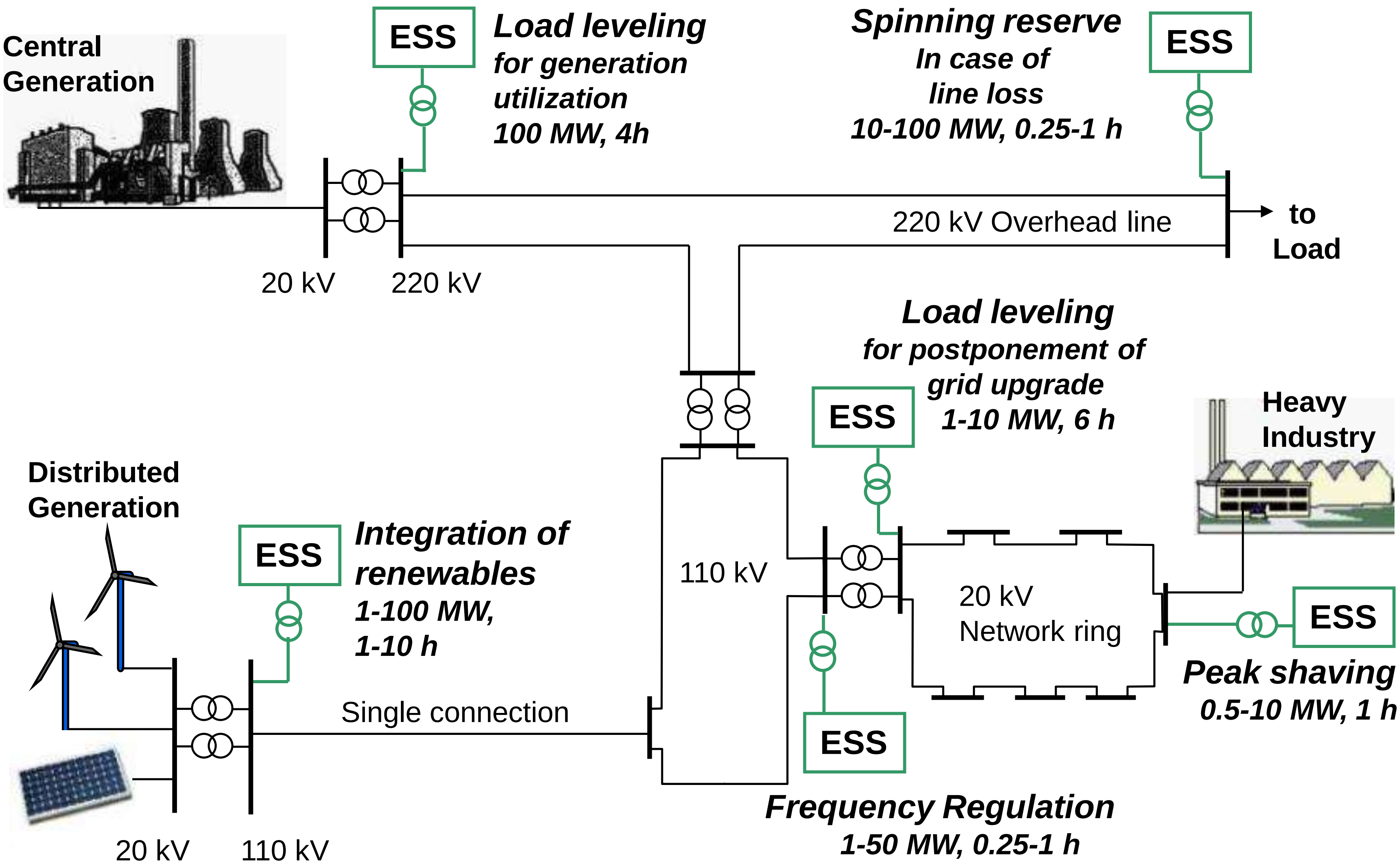
Battery Energy Storage Solutions
Applications and corresponding Technologies



Battery Energy Storage Solutions for the Smart Grid
Multiple applications – Power vs. Energy



Energy Storage System (ESS) Applications



Pumped Hydro Storage – The Main Player

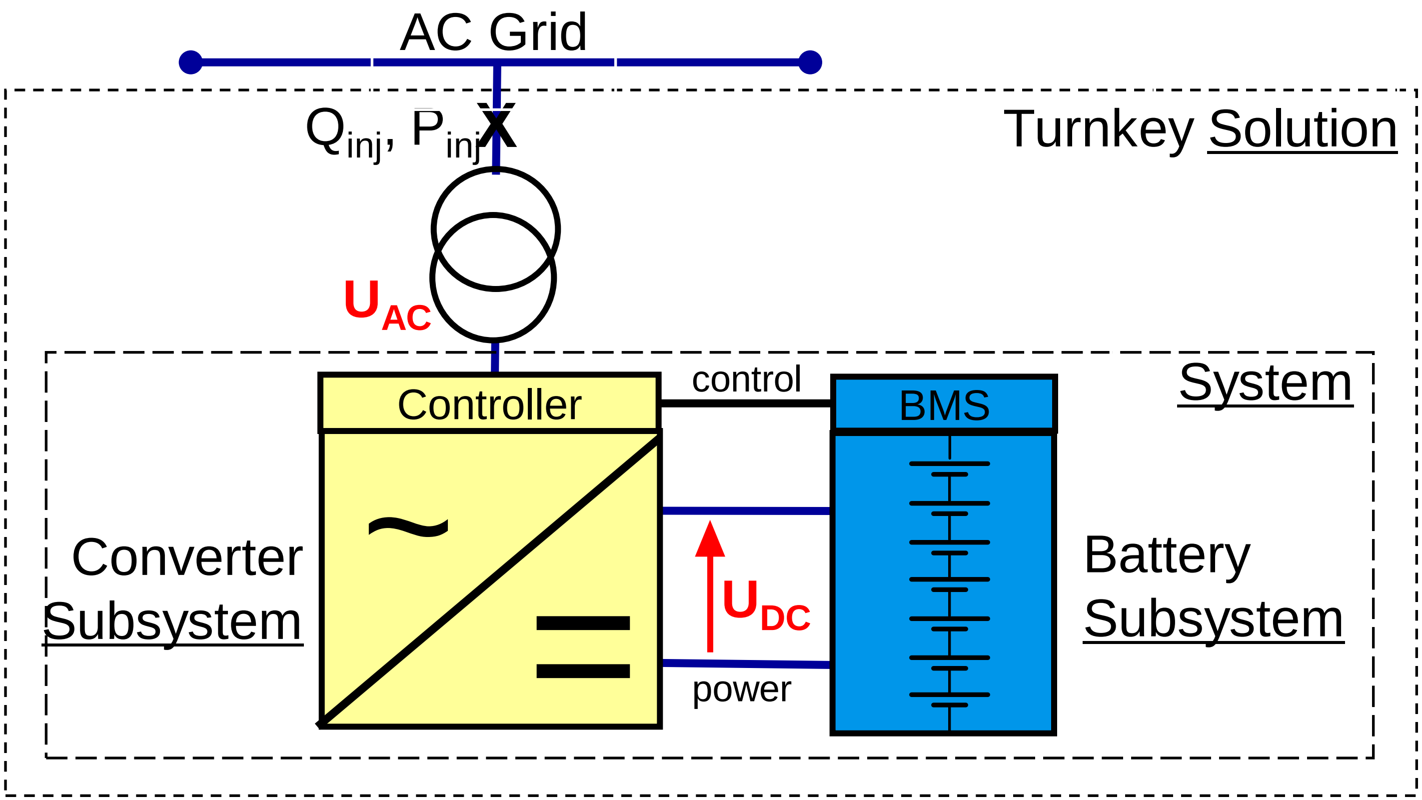
In total (worldwide):
≈100 GW installed capacity

Goldisthal (Germany)
1060 MW , 8480 MWh

- AC to AC efficiency = 80%
- Connected to Grid of VEAG
- Construction 1997-2002
- Cost: 600 Million Euro

© dpa

Battery Energy Storage System
System Architecture

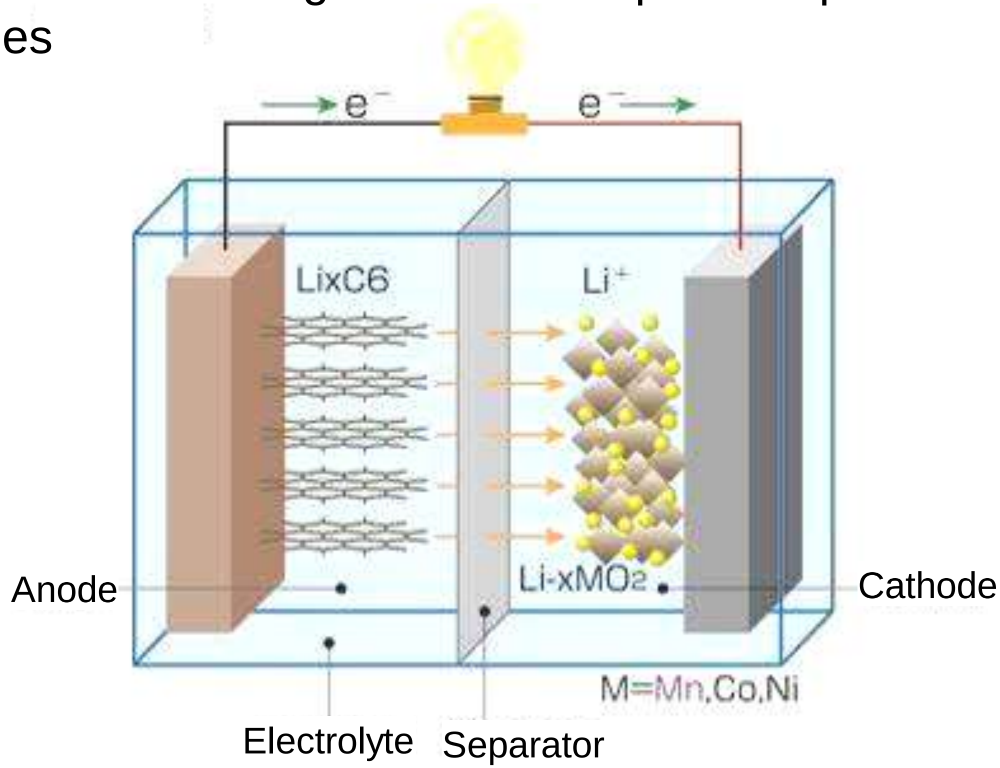


Functions:
1. Voltage Control Operation: Reactive Power Q_{inj}
2. Frequency Control Operation: Real Power P_{inj}
3. Load Leveling / Peak Shaving Operation: Active Power
4. Black Start / Stand-alone Capability

Battery Development
Example: Li-Ion Battery

Working principle:

- Lithium ions move between the electrodes
- Electrons flow through the outer loop to compensate the movement of charges



Prof. J. M. Tarascon (Amiens)

Li-Ion Battery Technology

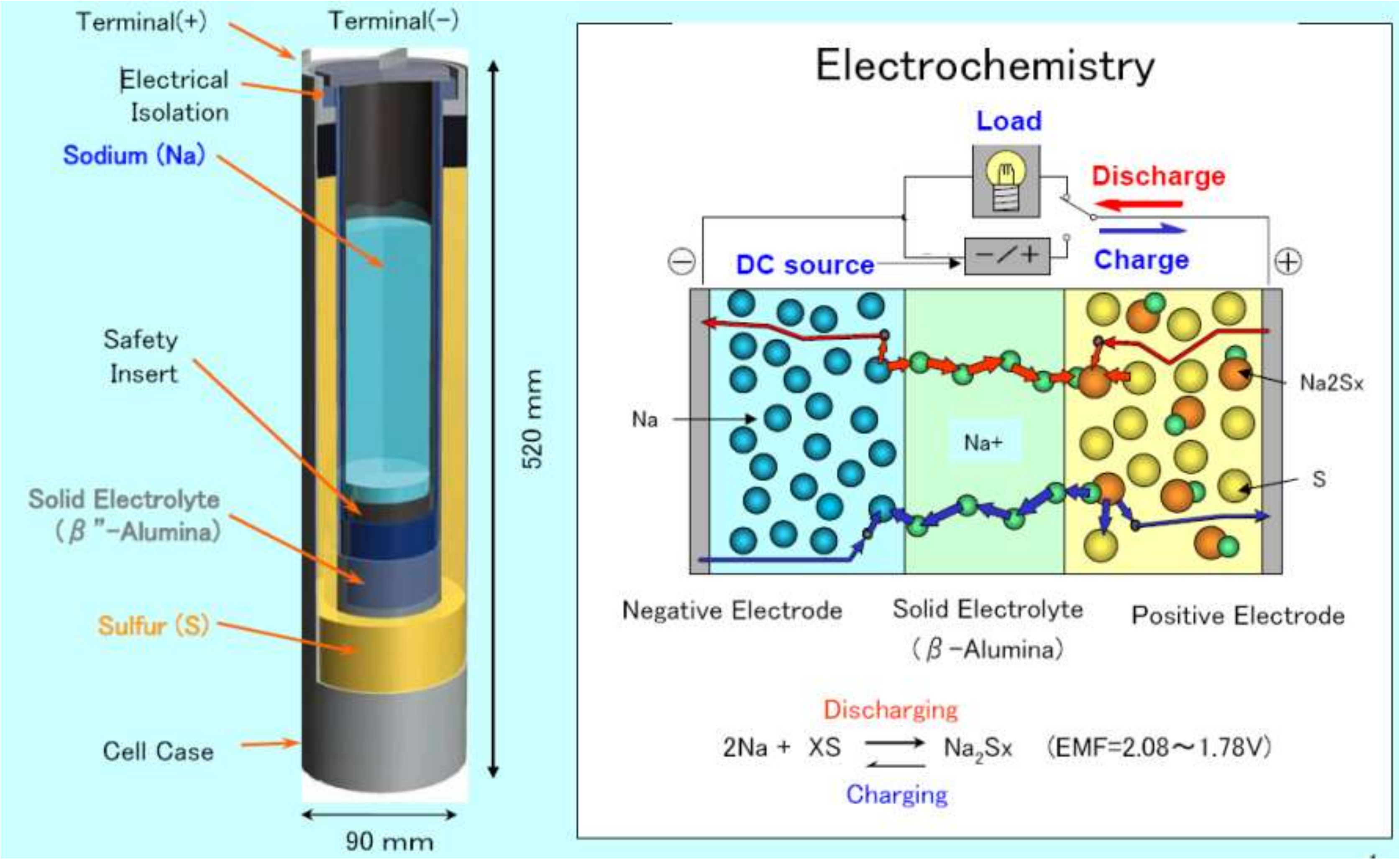
Advantages

- High specific energy
- High efficiency (90-95%, battery only)
- High open circuit voltage (cell)
- Long cycle life (up to 3000 cycles)
- Low stand-by losses (0.1-1%/month)
- No maintenance
- Many producers (especially for PHEV)
- Opportunity for cost reduction
- Large development potential (many new chemistries)

Disadvantages

- Today cost is high (1000-2000$/kWh)
- Mass manufacturing of large modules is not mature
- Safety issues for lithium-metal (thermal runaway)
- More complex battery monitoring system (charging and discharging equilibration)

Sodium Sulfur Battery (NaS)
Working Principle



Sodium Sulfur Battery (NaS)

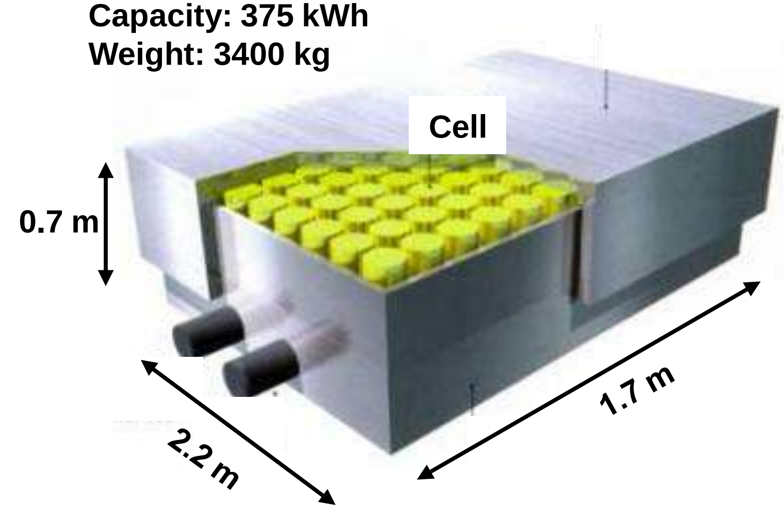
Advantages

- Abundant and low cost raw materials
- Proven reliability: > 200 large installations (Japan)
- Excellent life time: 15 years, 4500 cycles for nominal cycles
- Compact: High energy density of module: 124 Wh/l (same as Li-Ion modules)
- Battery containers – no need for dedicated building

Disadvantages

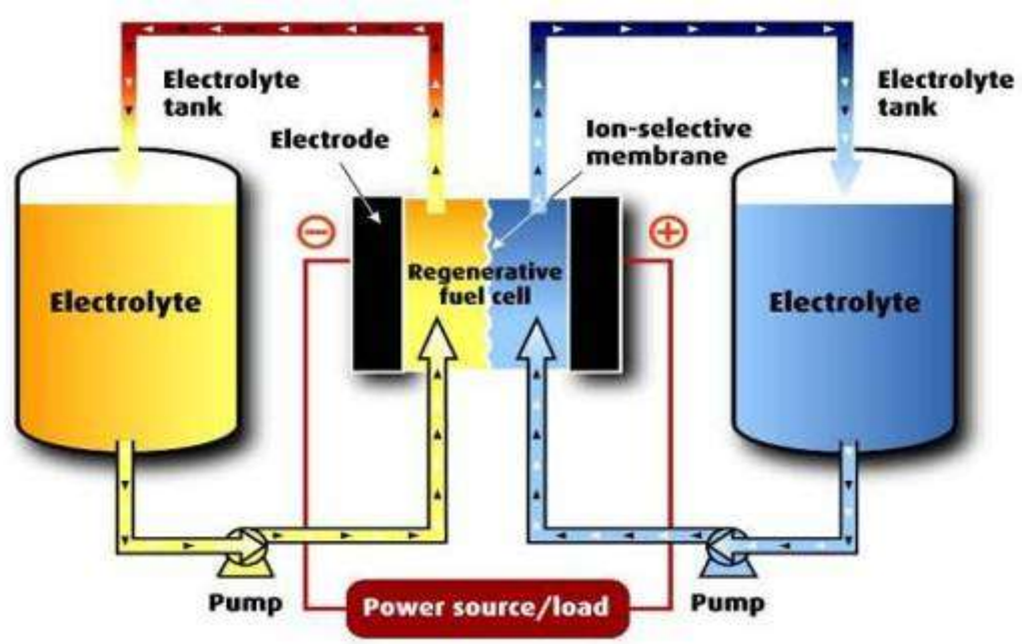
- Very difficult to produce the high grade ceramics → sole manufacturer is NGK in Japan
- High temperature: runs at 330°C
- Only limited cool downs permitted (around 20)
- Low power density of 21 W/l → fast discharge is not possible

50 kW Battery Module
Capacity: 375 kWh
Weight: 3400 kg



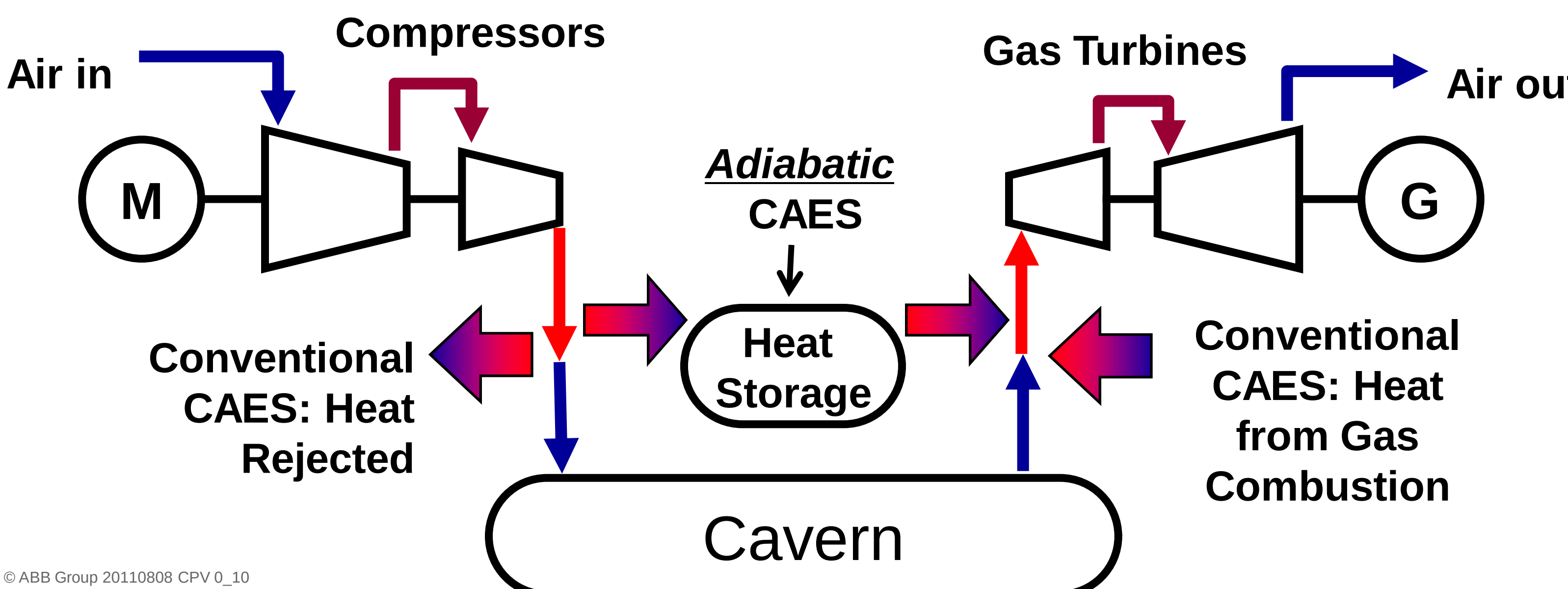
Redox Flow Battery
Working Principle

- Relatively new technology
- Efficiency 70%
- Low power density
- Indicative capital cost:
  1.5 – 3.1 kUSD/kW
- Charge/Discharge time typically up to several hours
- Capacity is given by the Electrolyte volumes (and concentration)
- Power is given by the Electrodes (surface area, structure, material)



Compressed Air Storage (CAES)

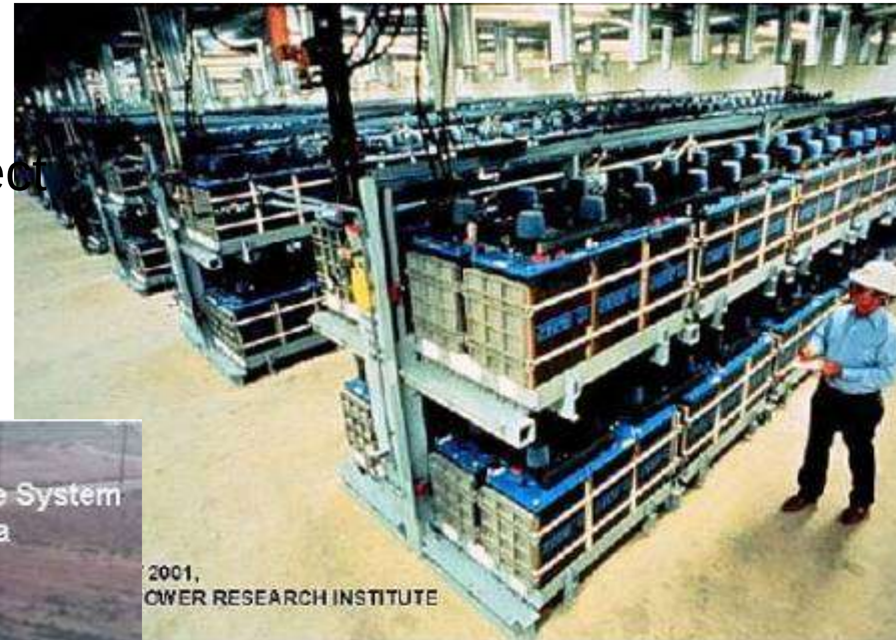
- Huntorf (1978), McIntosh (1991)
- Alstom: EU project on Adiabatic CAES
- Target Costs: 12 €/kWh + 1200 €/kW

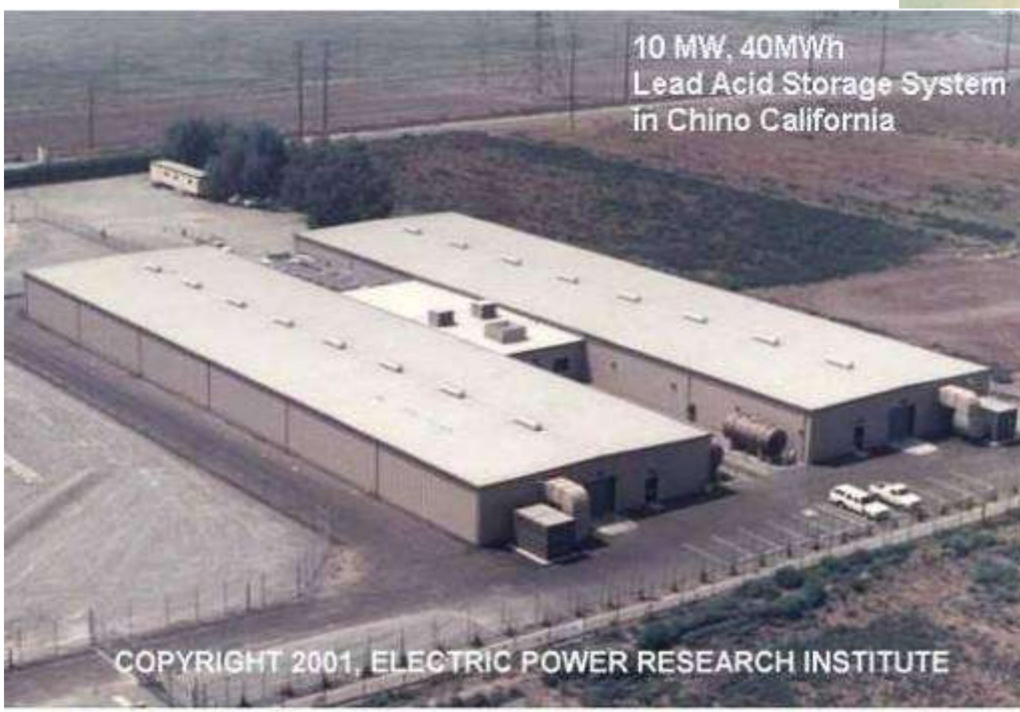


Lead Acid Battery Energy Storage System
Example

Battery Storage Demonstration Project

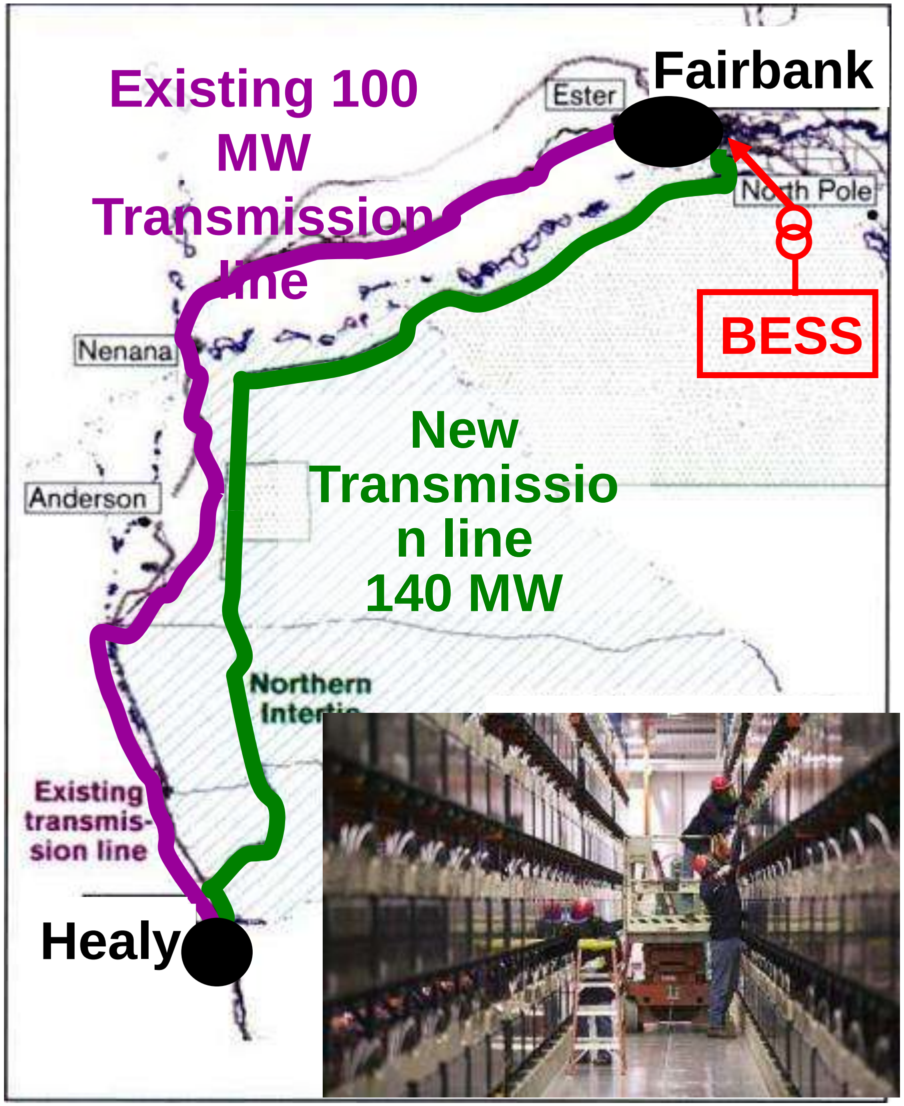
- Construction: 1986-88
- Operation: 1988-97





- AC to AC efficiency: 72%
- Cost: 18.2 M US$

Ni-Cd BESS Golden Valley Electric Association, Alaska, USA
Example



System Supplier:

- ABB in Cooperation with SAFT
- Cost: 35 million US$

In operation since 2004

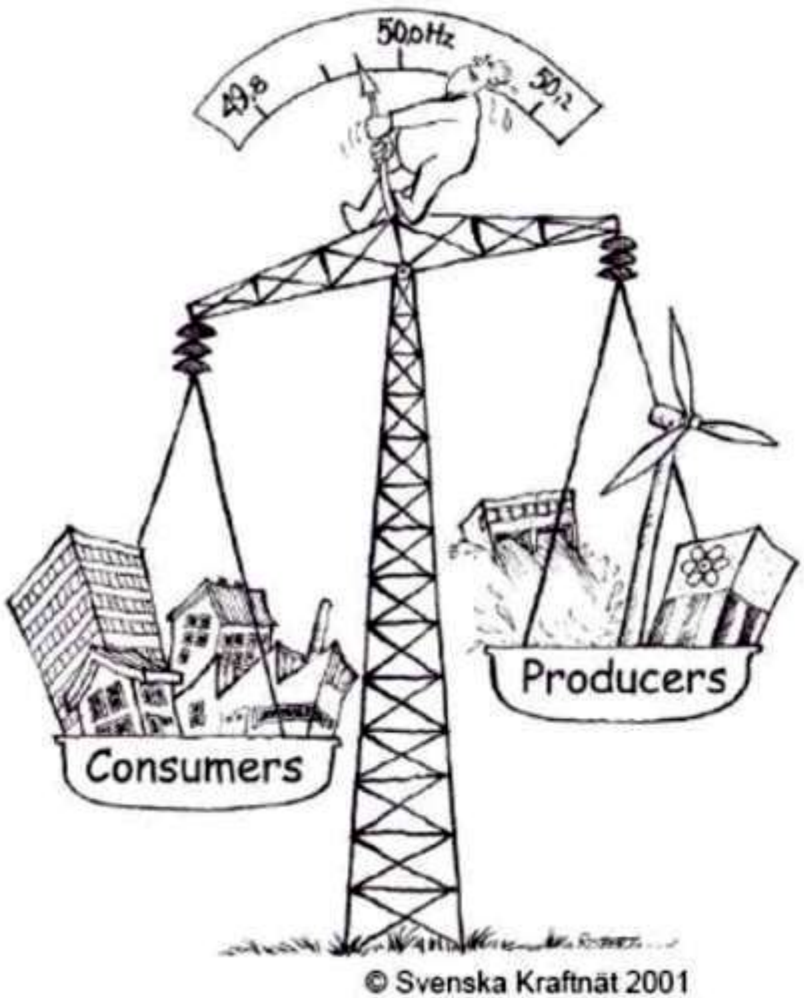
Specification:

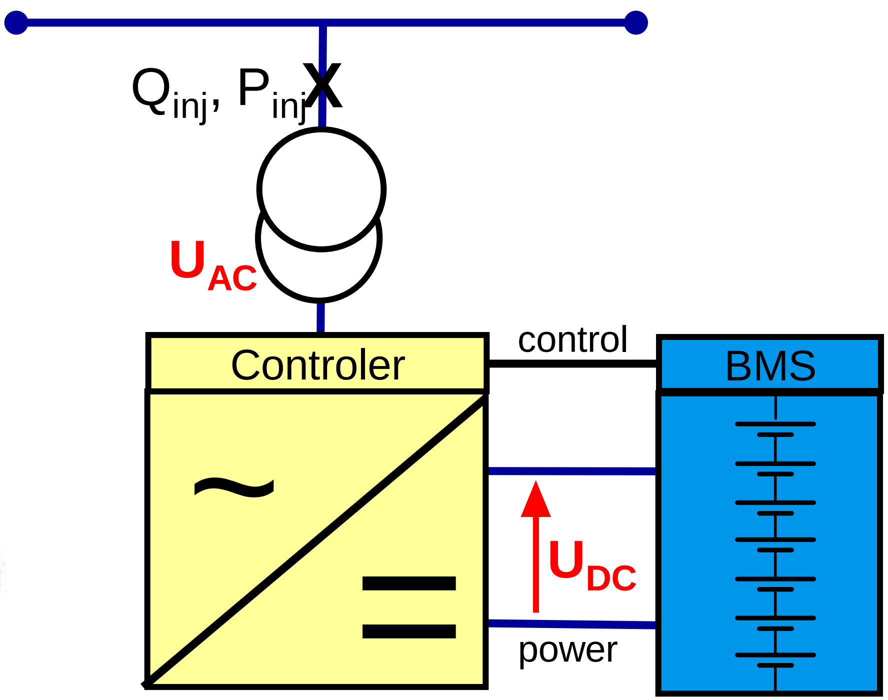
- 40 MW for 7 min (4.7 MWh)
- 27 MW for 15 min (6.75 MWh)
- AC to AC efficiency ≈ 75%
- Battery life time: 20 years

Applications:

- Backup Power in case of line loss
- Spinning reserve
- Reactive power compensation

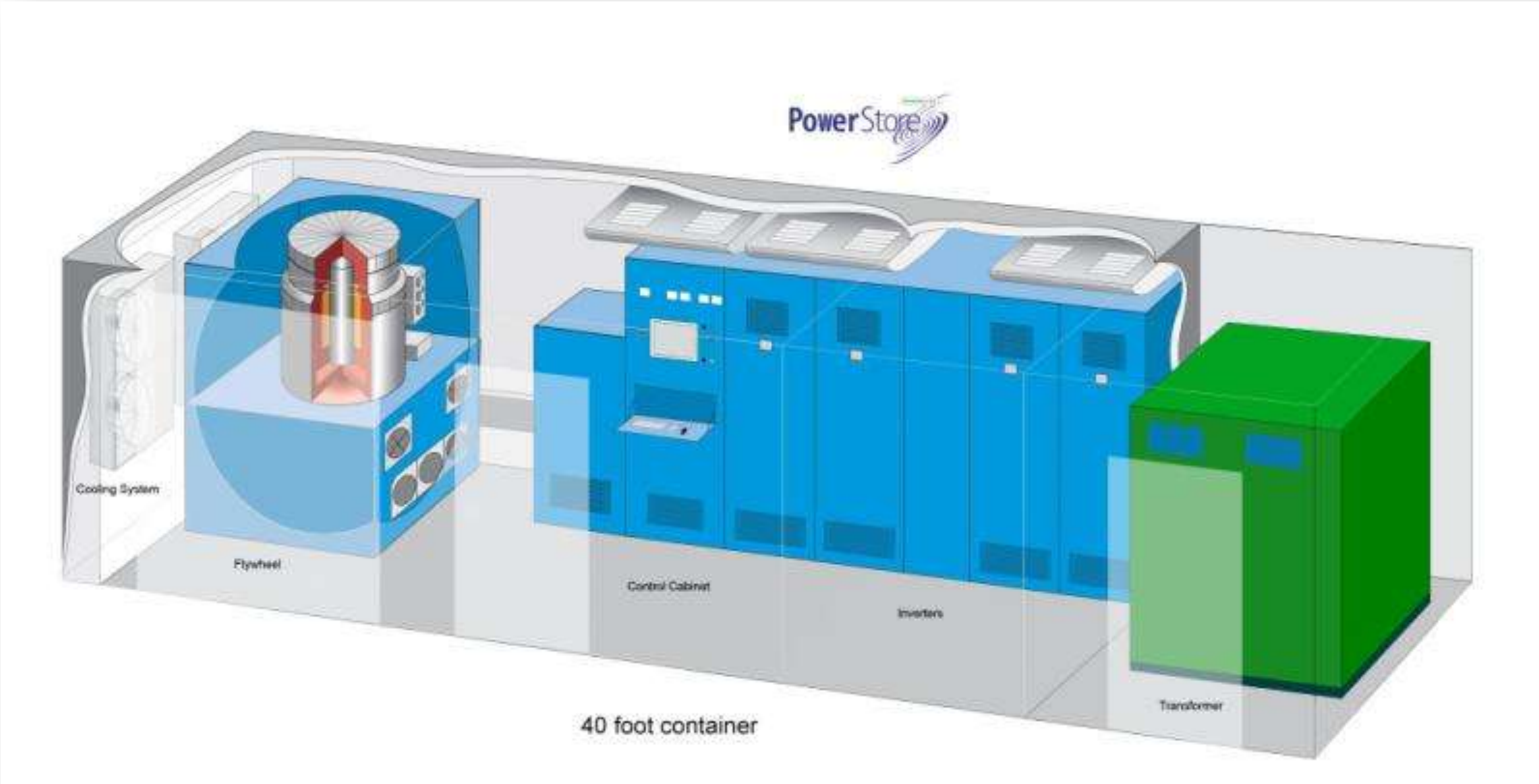
Primary Frequency Regulation





Function:
Frequency Control Operation:
Real Power P_{inj} injection/extraction

Frequency Regulation
Flywheel containers



Applications

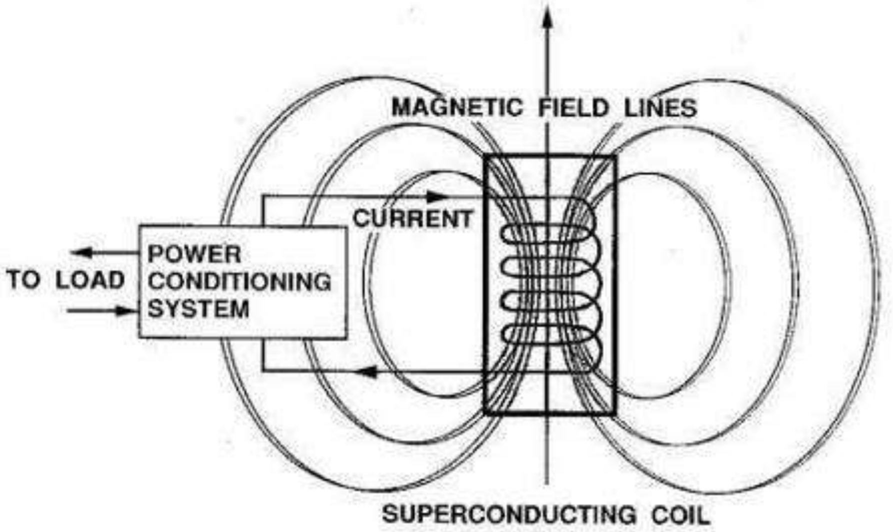
- Telecom (500 000 h of operation)
- Frequency control
- Reactice power
- Renewable ramp mitigation

- Peak Lopping
- Frequency Regulation
- Renewable Only Generation
- System Spinning Reserve
- Start-up assistance of large loads

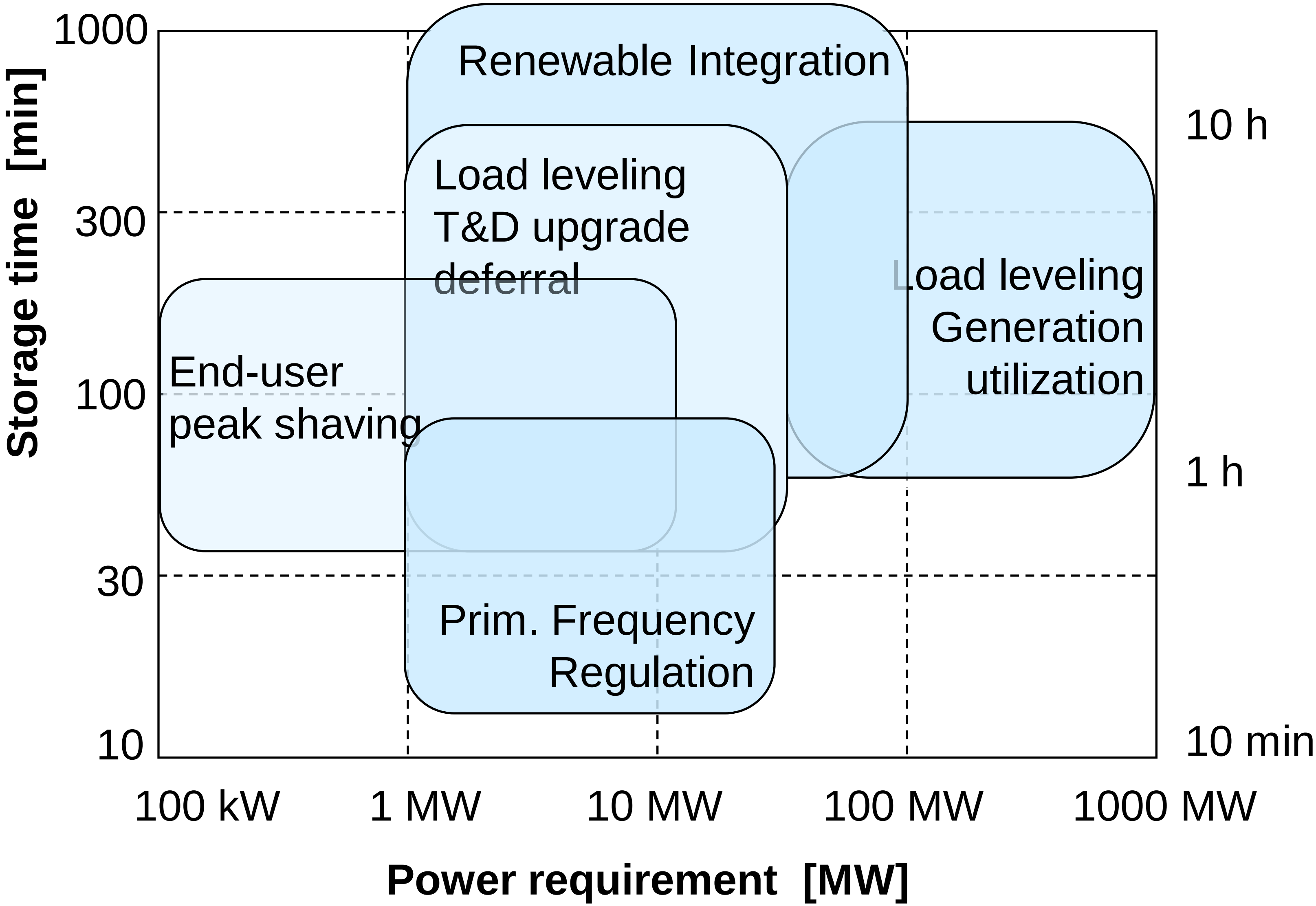
Superconducting Magnetic Energy Storage (SMES)

Advantages
- Excellent cycle life
- Excellent calendar lifetime
- High power delivery (limited by power conversion system)
- High AC to AC efficiency (>90%)

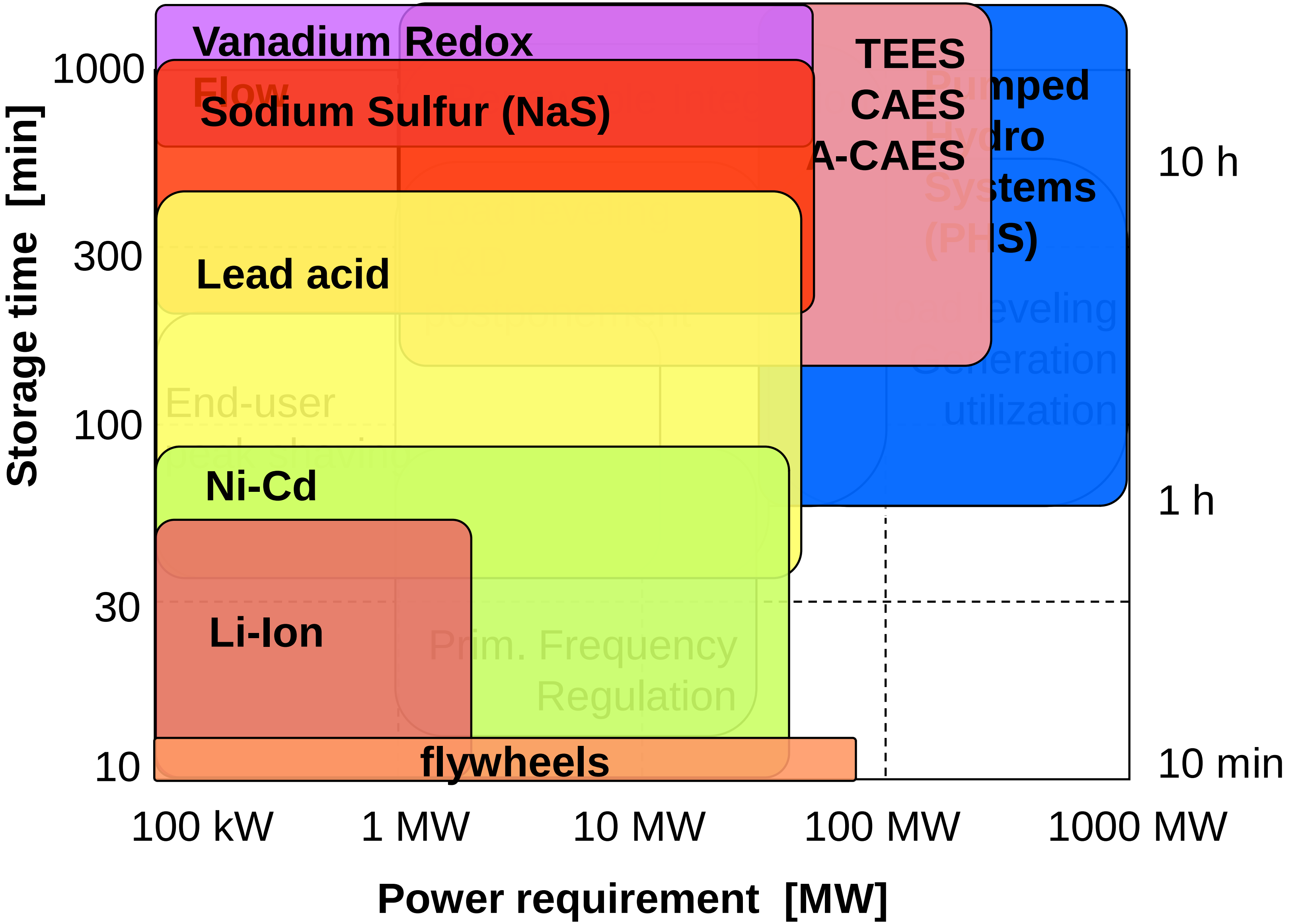
Disadvantages
- High energy storage costs ($/kWh)
- Plants with larger than 1MWh were never built
- Cooling system



Applications



Applications and Corresponding Technologies



Energy Storage Technologies

Storage Technologies	Main Advantages (relative)	Disadvantages (Relative)	Power Application	Energy Application
Pumped Storage	High Capacity, Low Cost	Special Site Requirement		●
CAES	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries: PSB VRB ZnBr	High Capacity, Independent Power and Energy Ratings	Low Energy Density	◐	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	●	●
Li-ion	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy Densities, Efficiency		●	◐
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when Deeply Discharged	●	○
Flywheels	High Power	Low Energy density	●	○
SMES, DSMES	High Power	Low Energy Density, High Production Cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy Density	●	◐

Battery costs

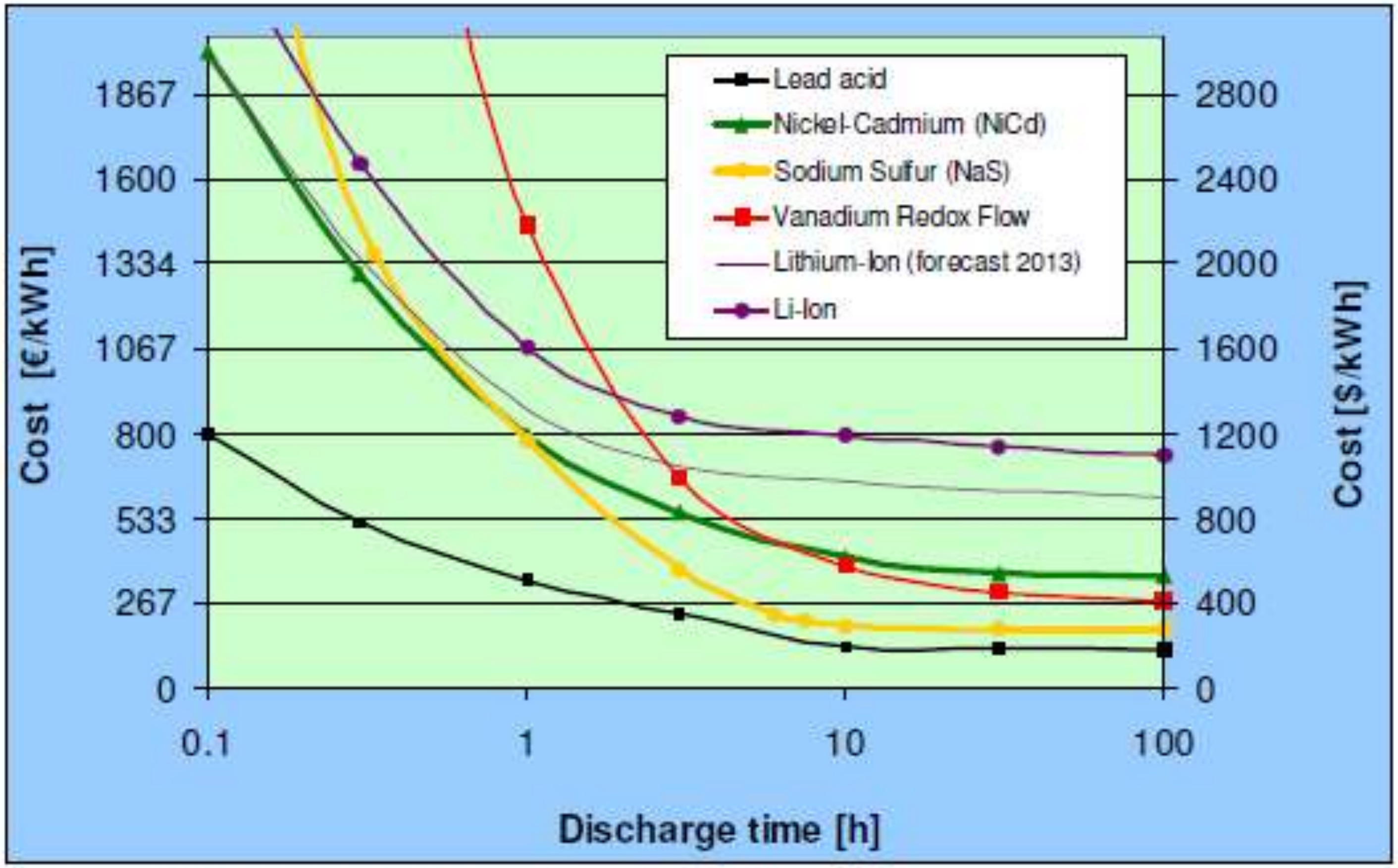


Figure 14: Battery cost vs. discharge time.

Battery costs

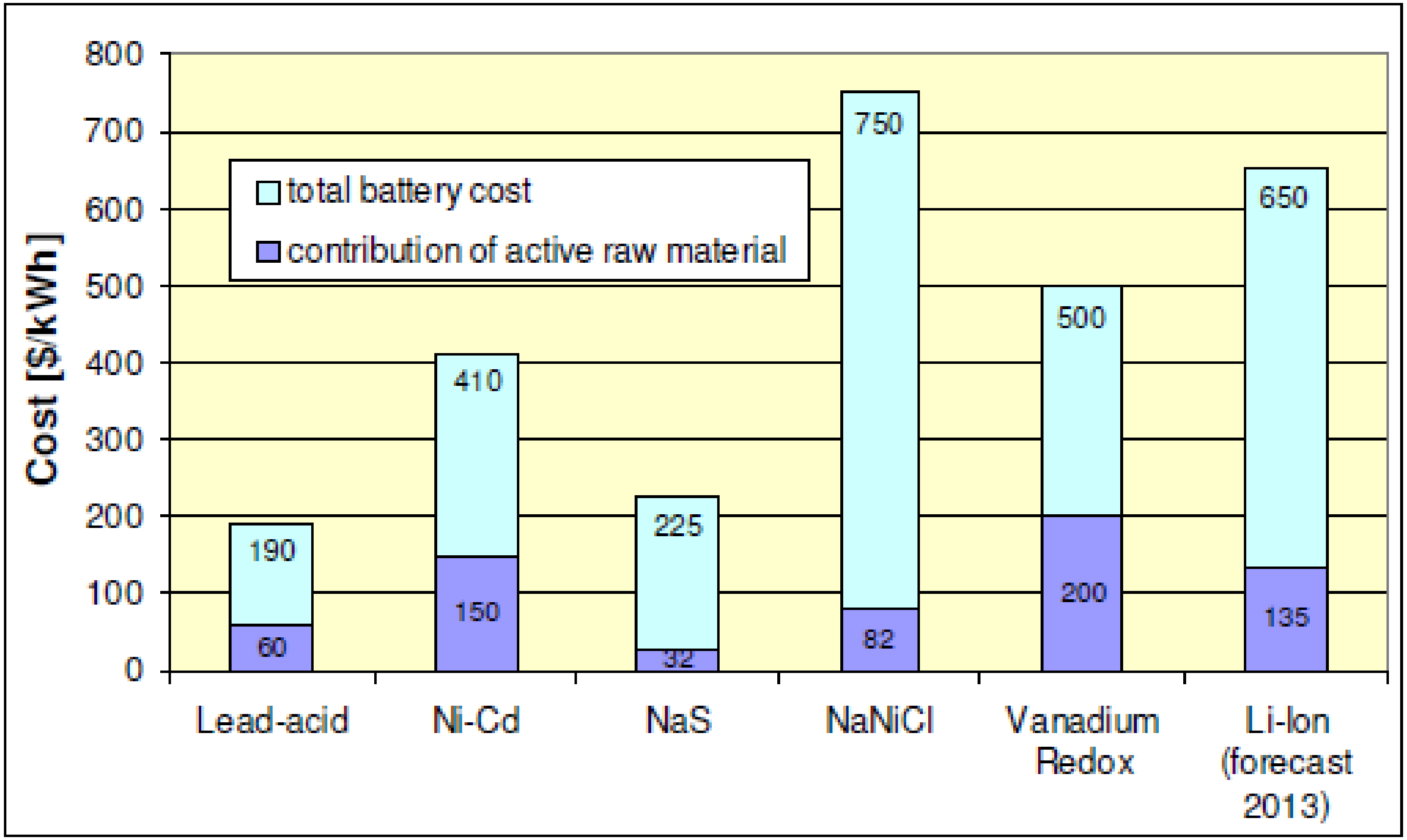


Figure 15: Estimated raw material cost based on per kWh quantities, 2008 [12]:

Energy Storage for CSP.
Current status

Heat storage allows a solar thermal plant to produce electricity under conditions like nights, cloudy days or weather perturbations

Storage allows CSP to become dispatchable.

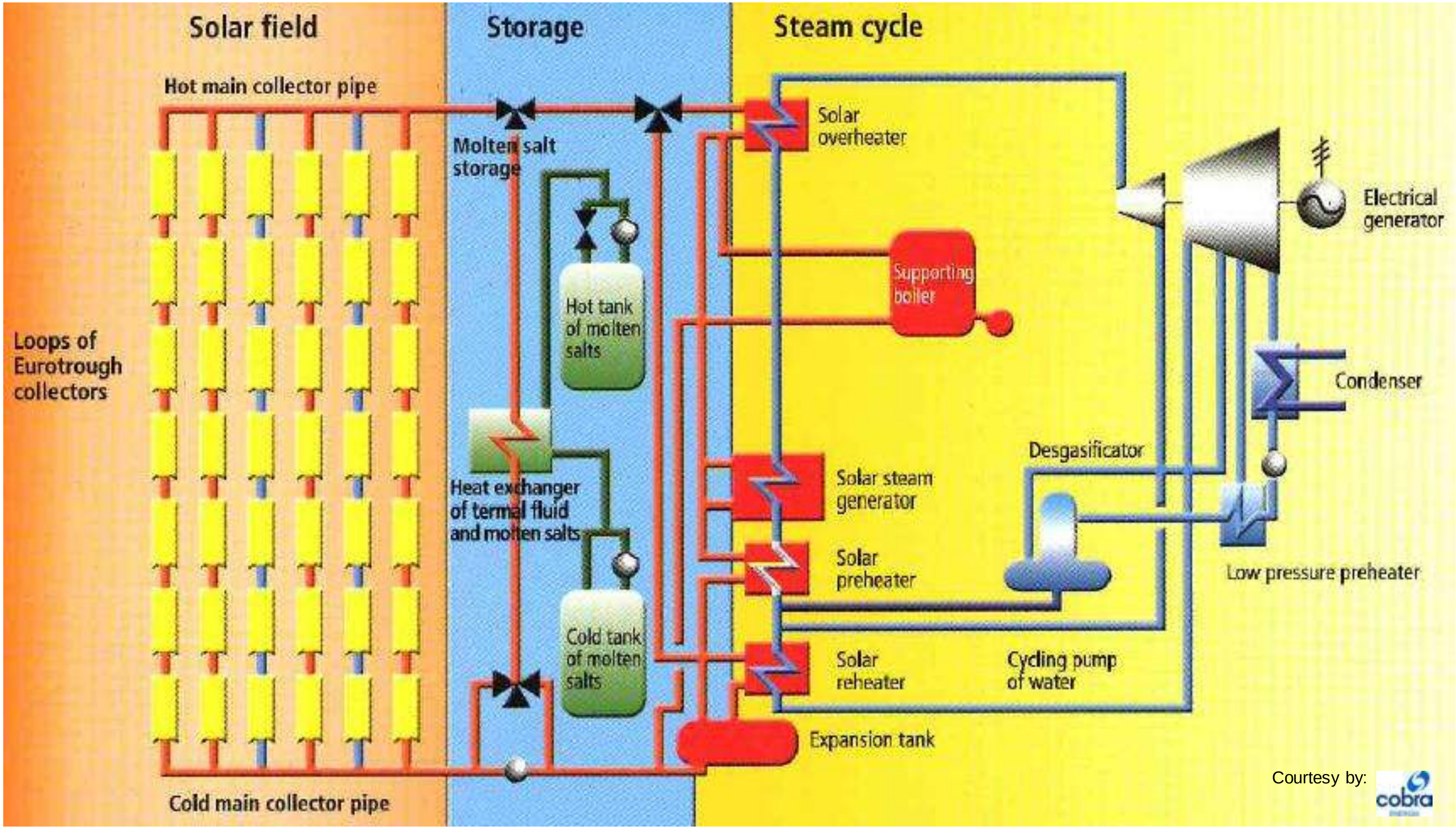
The cost of electricity is decreased and annual capacity factor is increased

Then the CSP plant becomes a baseload power plant as well as peak power generation.

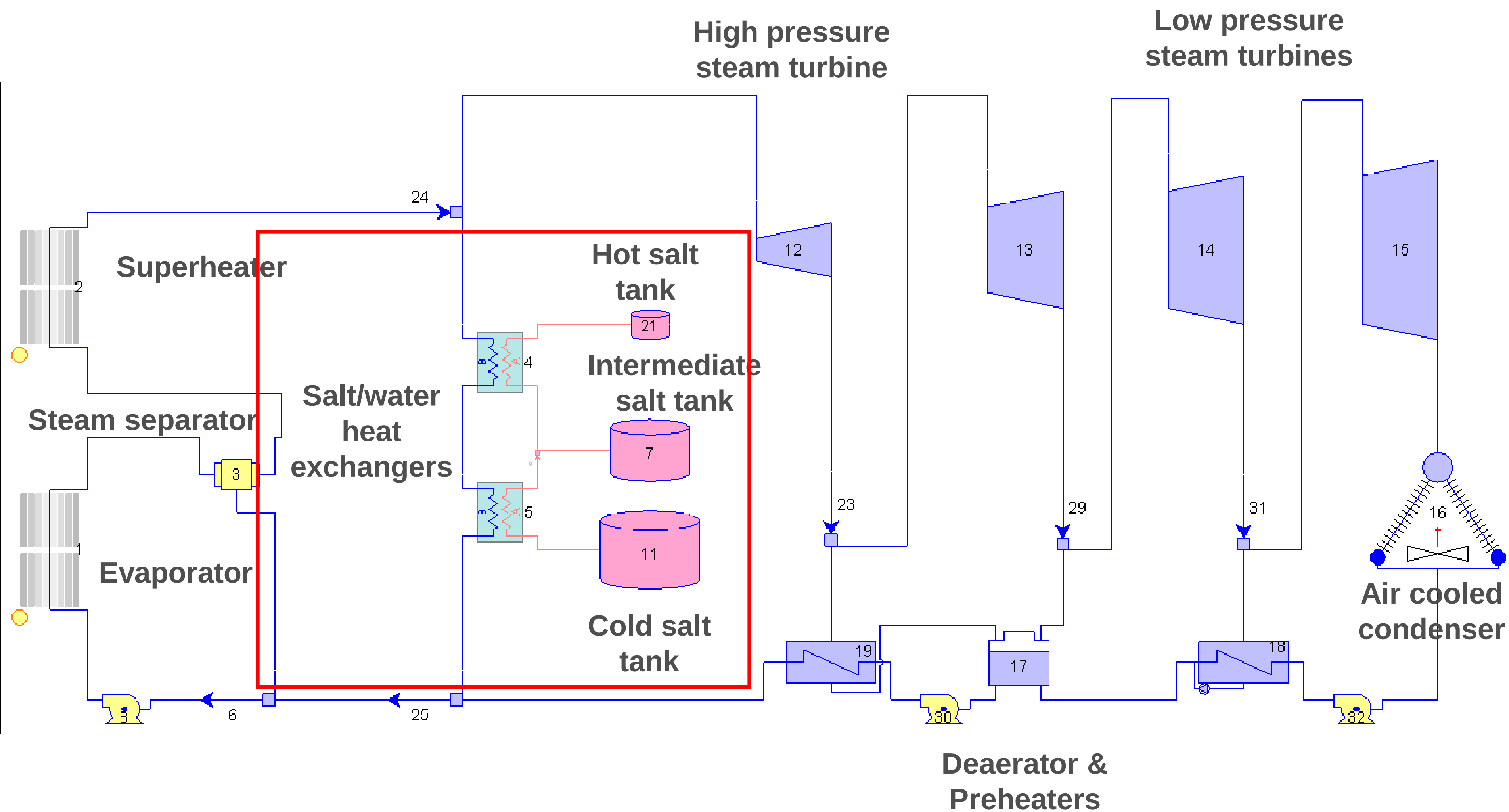
Heat is transferred to a thermal storage medium in an insulated reservoir during the day, and withdrawn for power generation the defined conditions

- Molten salt storage
- Steam accumulator
- Graphite heat storage
- Phase-change materials for storage
- Thermocline single-tank molten salt
- Ceramics
- Concrete

Thermosolar Power Plant Concept
Storage in Molten Salts



Superheated Power Plant Design with Molten Salt Storage



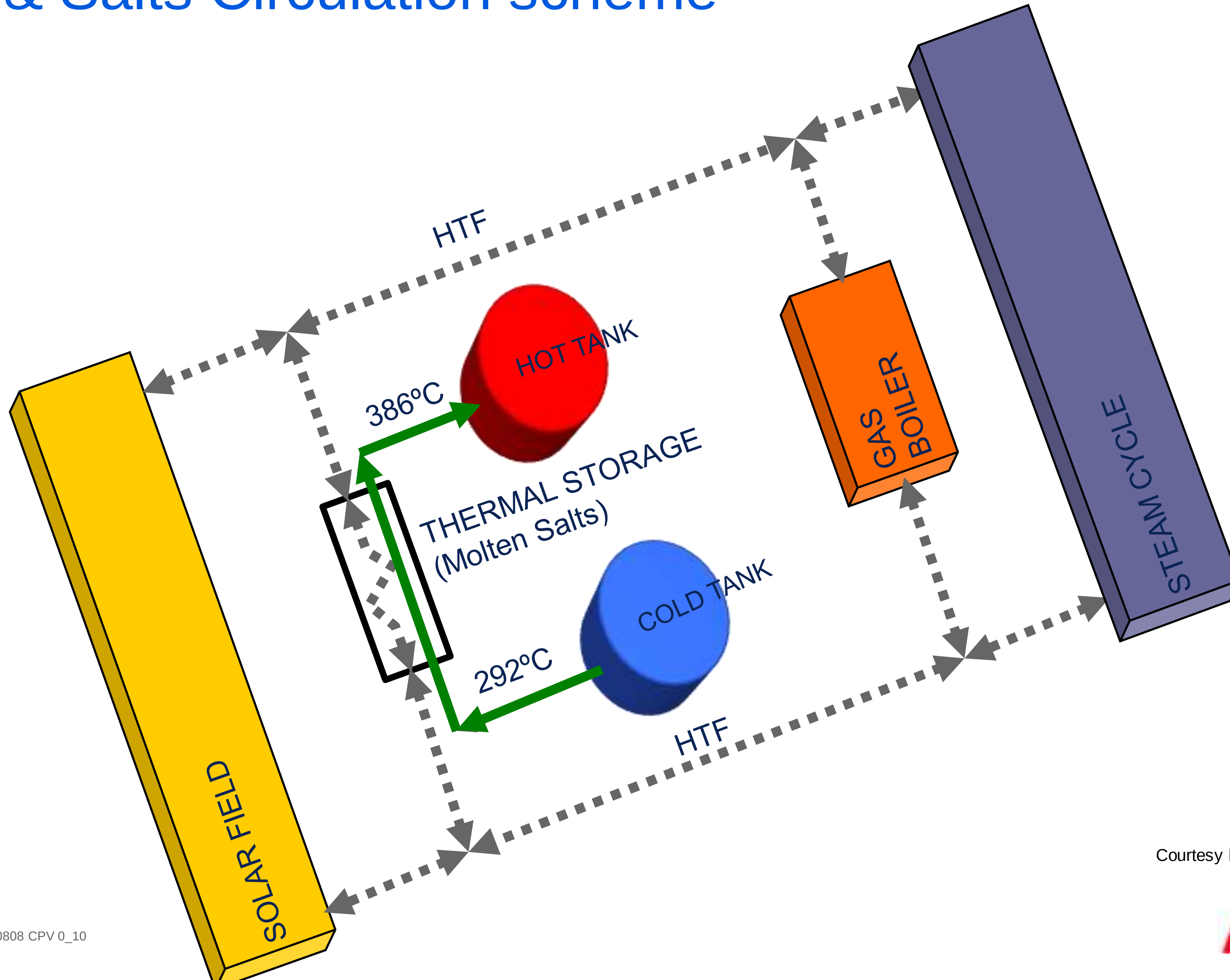
Thermosolar Power Plants
StorageTanks

Courtesy by: cobra

Thermal Energy Storage design
Spanish Power Plants Case Study

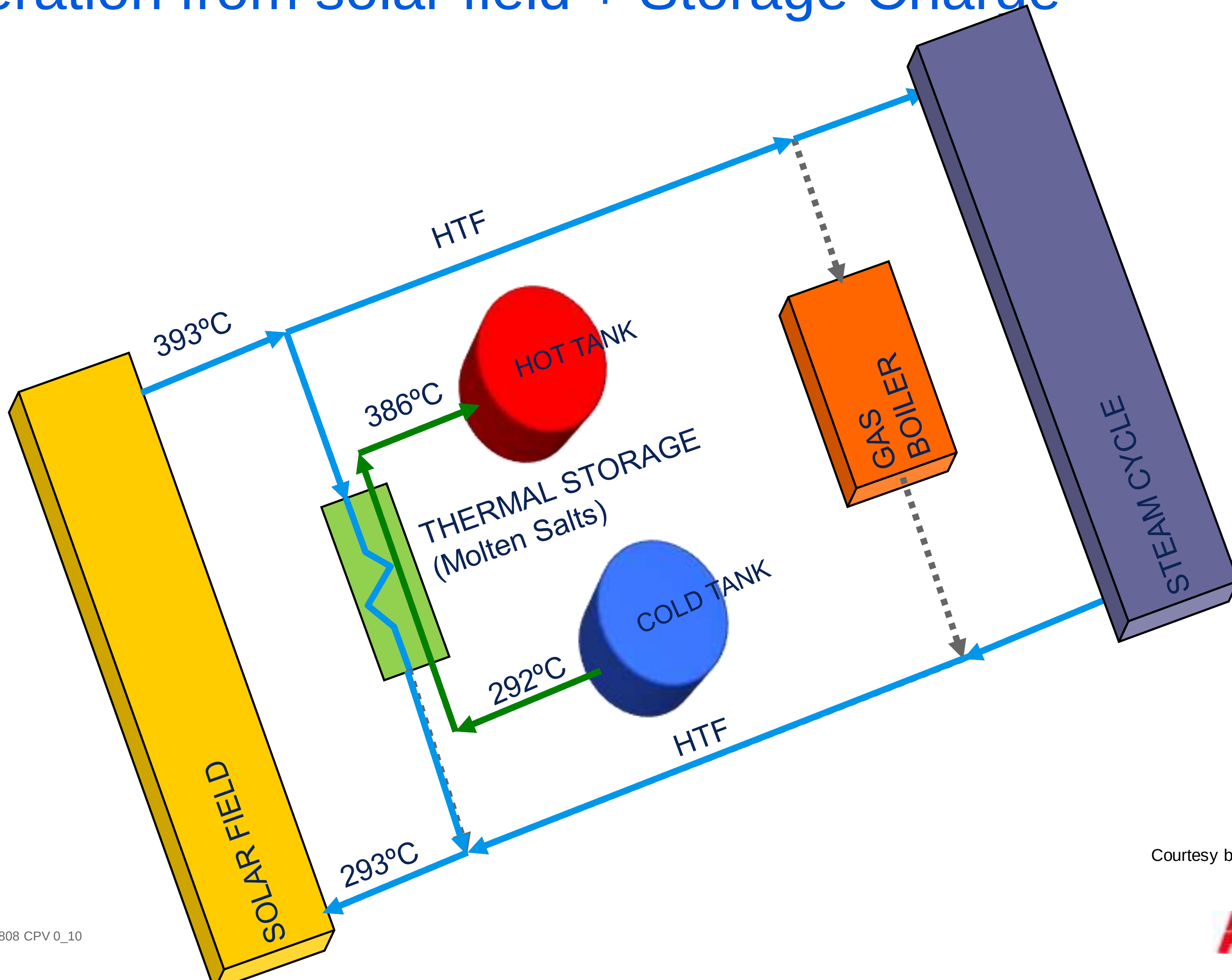
- Tank Size: 14 m height, 38 m diameter
- Salt Mass: 28,000 tons
- Cold Temp: 290°C
- Hot Temp: 386°C
- Melting Point: 221°C
- Fluid: Nitrate salt mixture (60% $NaNO_3$ and 40% KNO_3)
- Dispatchablility of production schedule: Reliable > 90% (24 h) ; > 95% (6 h)

Working Principles in a TES Power Plant
HTF & Salts Circulation scheme



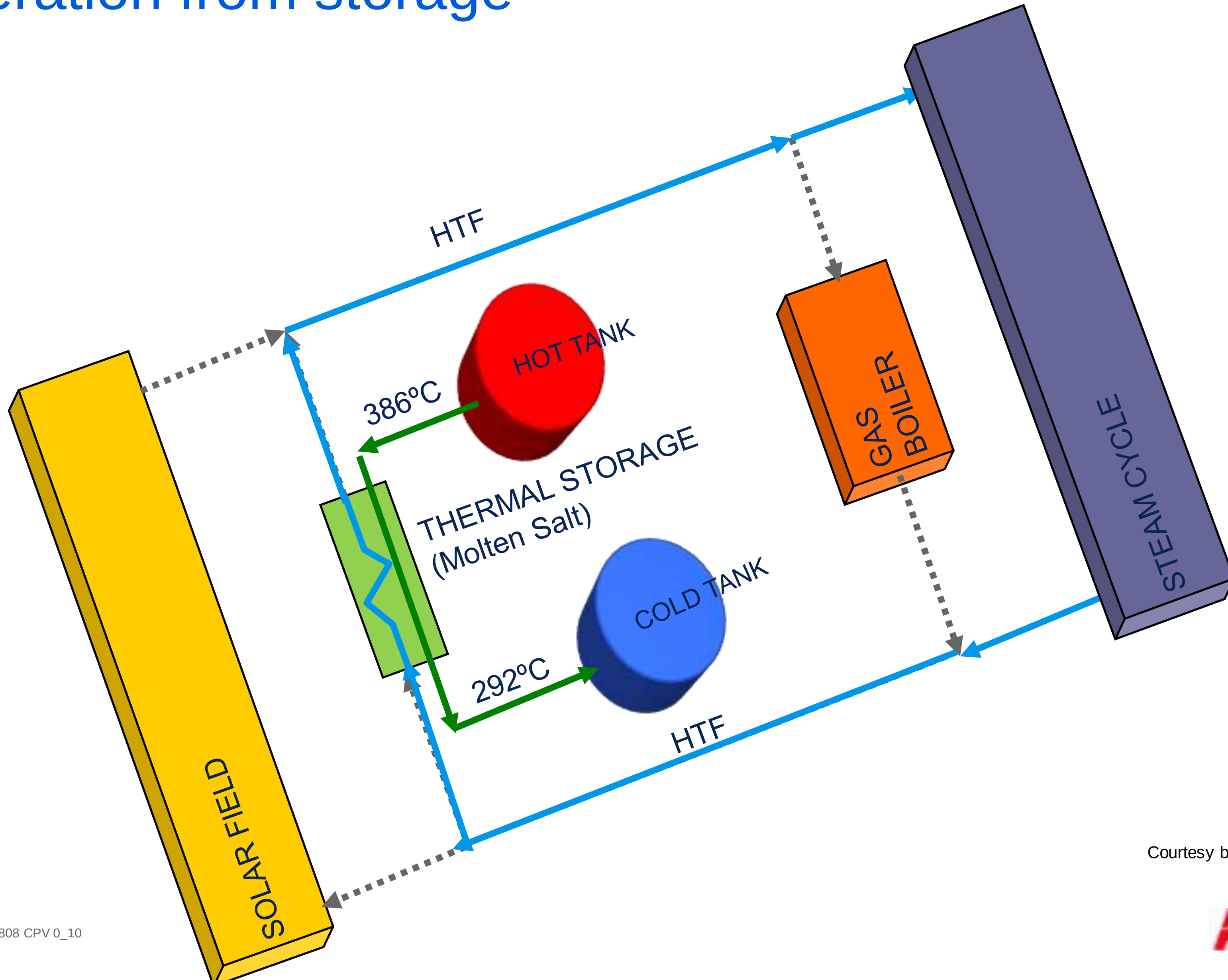
Courtesy by: cobra

Working Principles in a TES Power Plant
Generation from solar field + Storage Charge



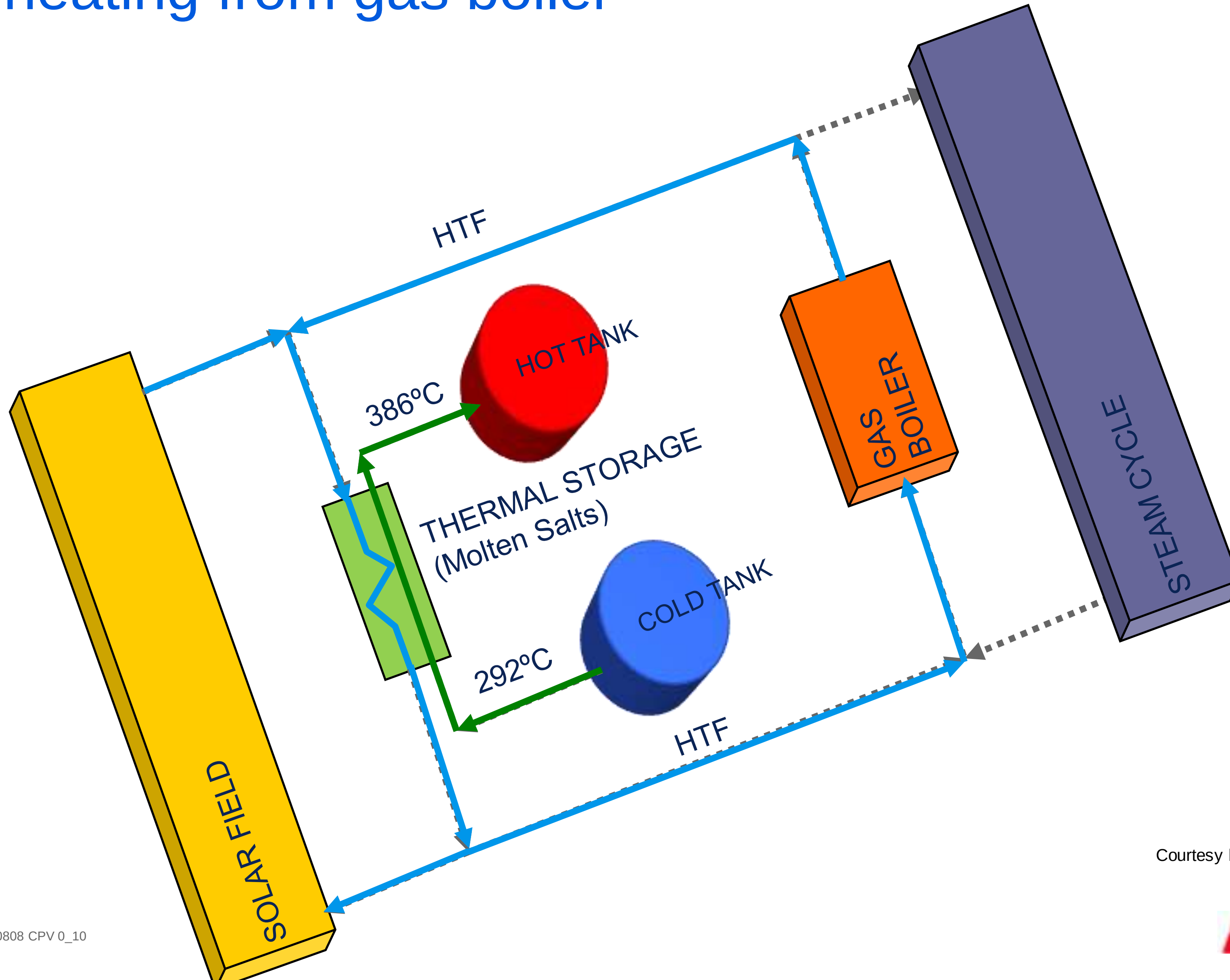
Courtesy by:

Working Principles in a TES Power Plant
Generation from storage



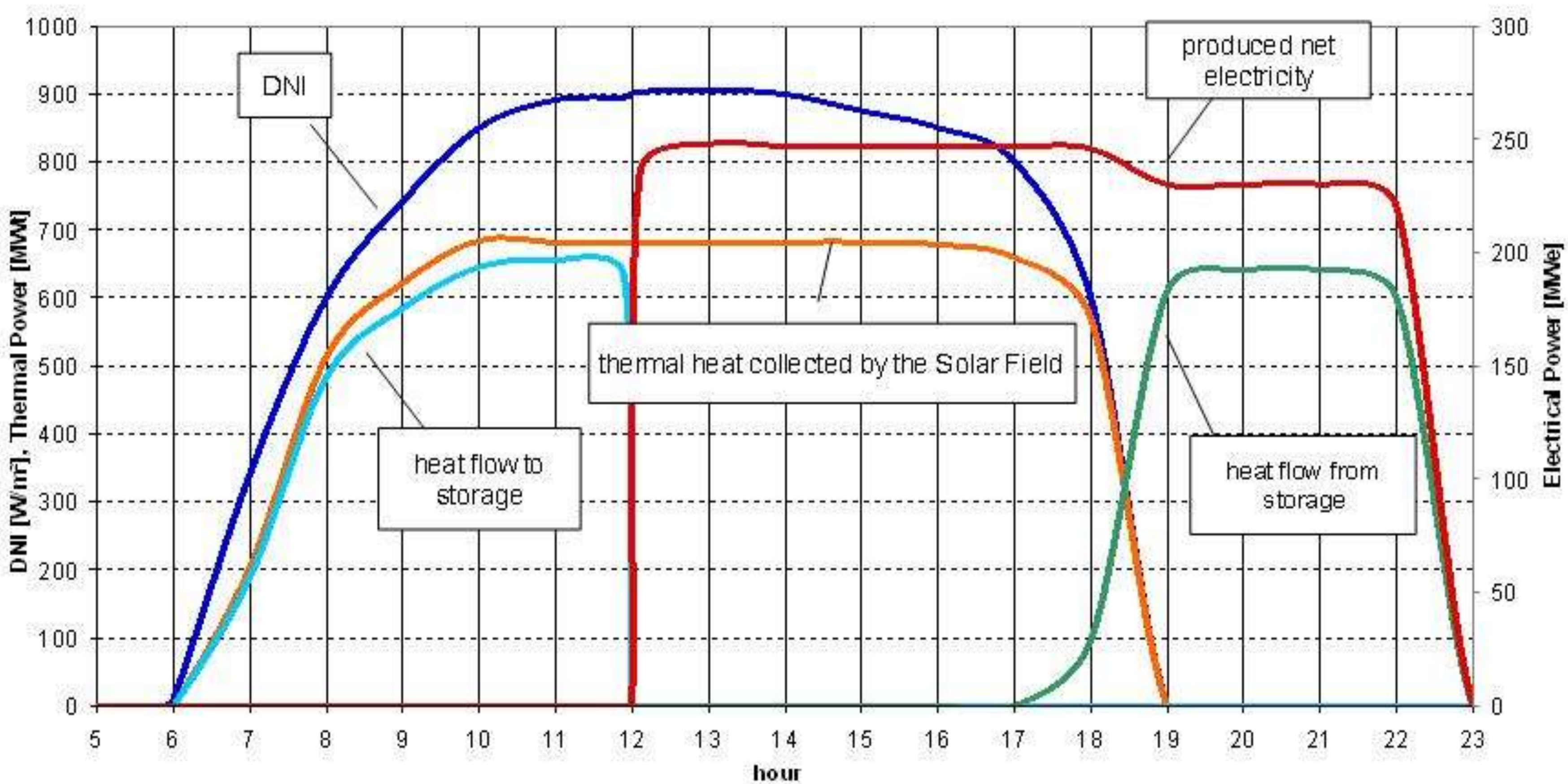
Courtesy by: cobra

Working Principles in a TES Power Plant
HTF heating from gas boiler



Courtesy by:

TES design criteria
Solar Multiple = 1 - Firm & Shifted Production



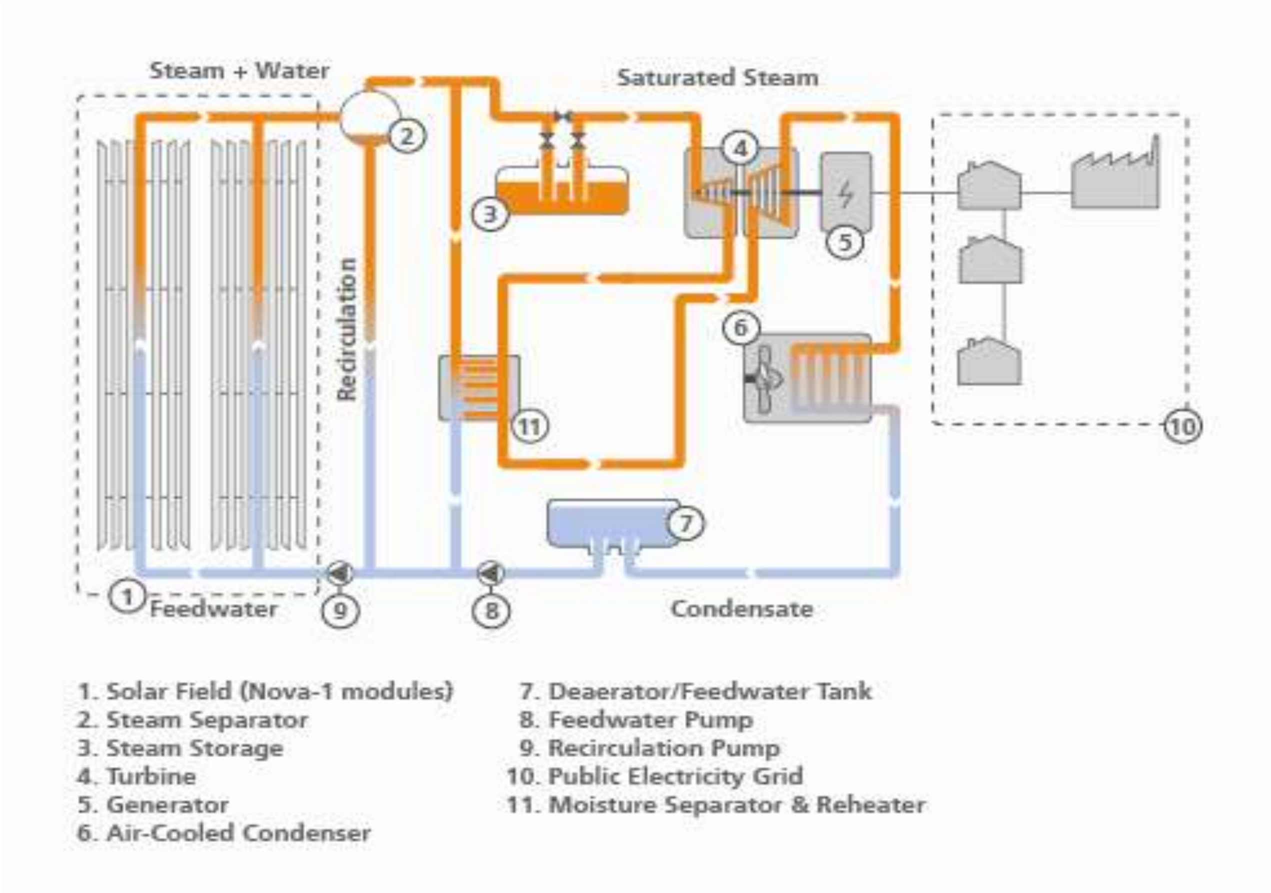
Courtesy by: cobra

Energy Storage for CSP.

Steam Acumulator

It is a direct method that directly stores the energy form the steam produced in a pressurized vessels stores as pressurized steam around 50 to 100 bar and 280 °C to 450ºC .

Storage capacity is depending on the size of the tank



Energy Storage for CSP.
Concrete storage

- Heat transfer fluid passes through a series of pipes embedded in concrete
- Key advantage is the low cost of the storage medium
- Key challenges: maintaining good contact between pipes & concrete as well as rate of heat transfer
- Current investment cost ~€30 / kWh, for large scale systems
- A 300 MWh storage system designed for a typical Spanish plant 50,000 m3 of concrete would be required

- Concrete storage module without insulation

- Concrete storage module with insulation

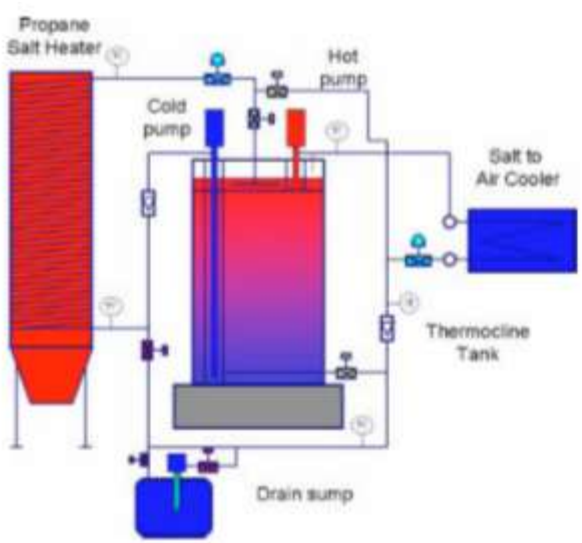
Energy Storage for CSP.
Pure Graphite

- Graphite blocks on top of towers heated directed by the sun via heliostats
- Graphite heated up to 800°C → very high energy density
- Pure graphite has the unique properties of being highly absorbent but with low emissivity (0.2)

- Receiver: high purity graphite thermal storage unit on top a 30m tower
- Heliostats: 2-axis tracking mirrors to concentrate sunlight upon receiver thereby heating up the graphite
- Water / steam system: Heat may be transferred on demand from the graphite to steam cycle system
- Controls: A DCS based control system that controls both heat input & output

Energy Storage for CSP.
Single tank thermocline

- One tank instead of two, hot fluid at the top cold at the bottom
- Most of the storage fluid can be replaced with a low-cost filler e.g. sand
- Difficult to limit extent of the thermocline zone within the tank



A thermocline single tank thermal storage system consists of:

- A single tank 70% filled with filler (e.g. sand, quartz) & 30% filled with molten salt
- A thermal gradient runs vertically through the tank: hotter fluid (lower density) is at the top & colder fluid is at the bottom

Applications

- Concrete storage may be added to any CSP plant & is relatively independent of heat transfer fluid
- A 1100 MWh storage system for a typical Spanish plant 252 basic storage modules each using 400 tons of concrete
- A ground surface are of ~300m x ~100m is required

Energy Storage for CSP.
Other Systems

Phase change materials

- Liquid to solid phase change that occurs at the same temperature as the liquid to gas phase change in the steam
- Latent heat associated with phase change is large
- Large amounts of energy stored in relatively small volumes → low costs

Ceramics & other solid materials are also being investigated for use as a storage medium

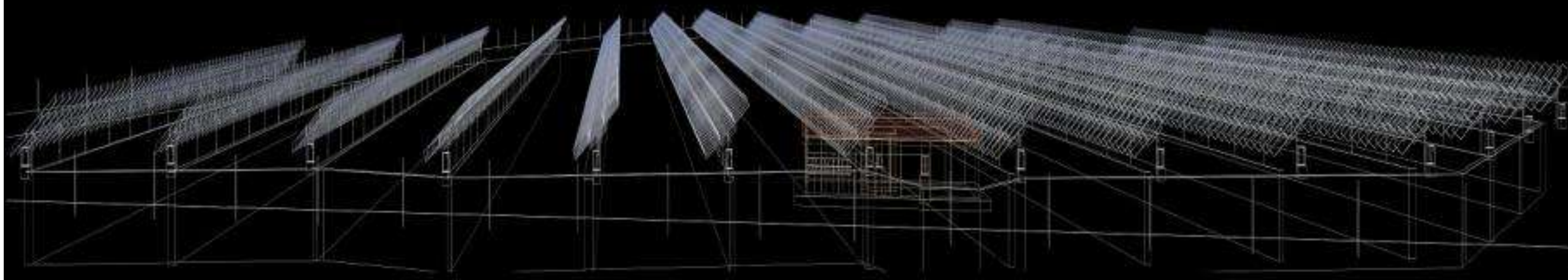
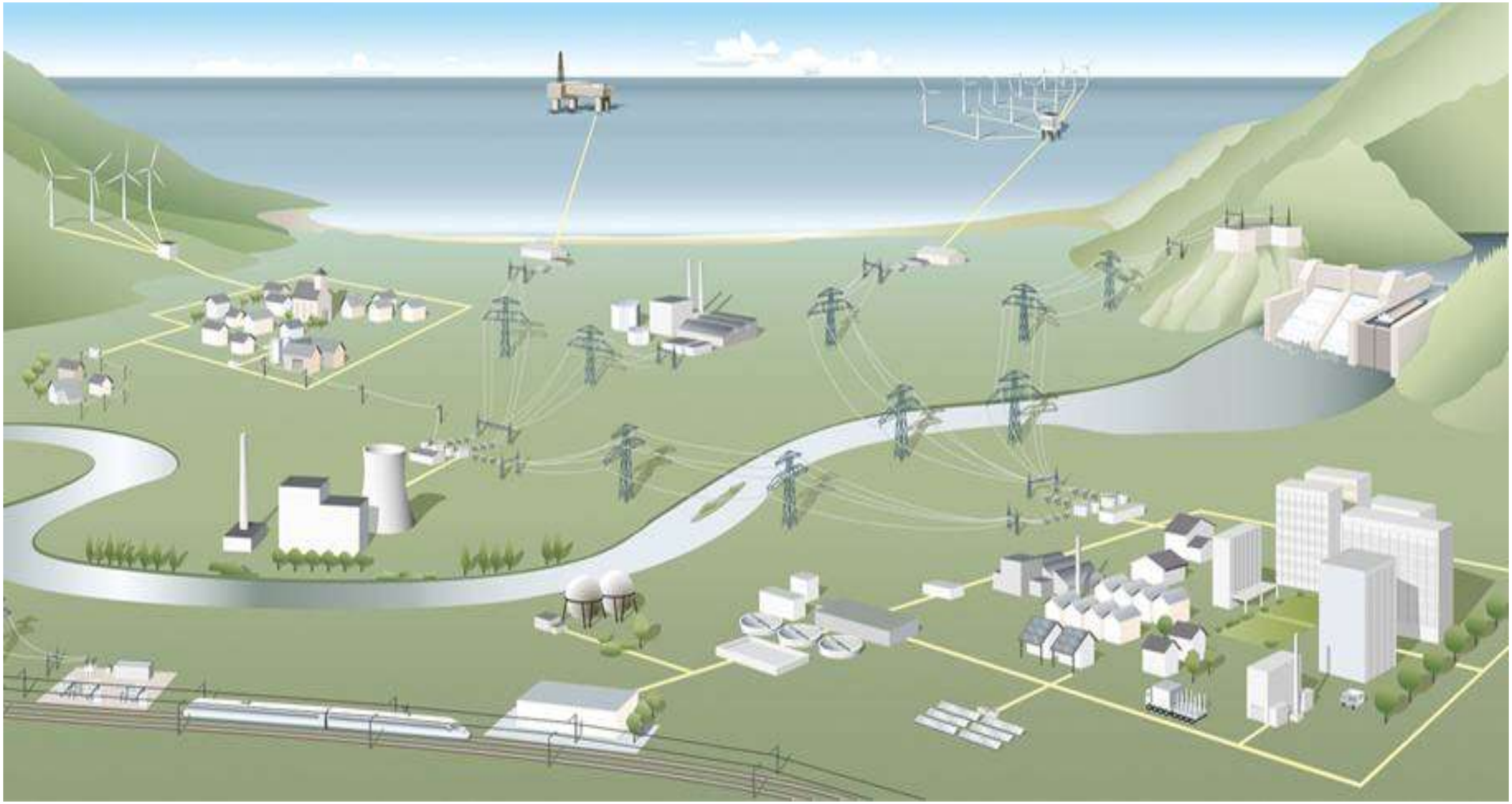


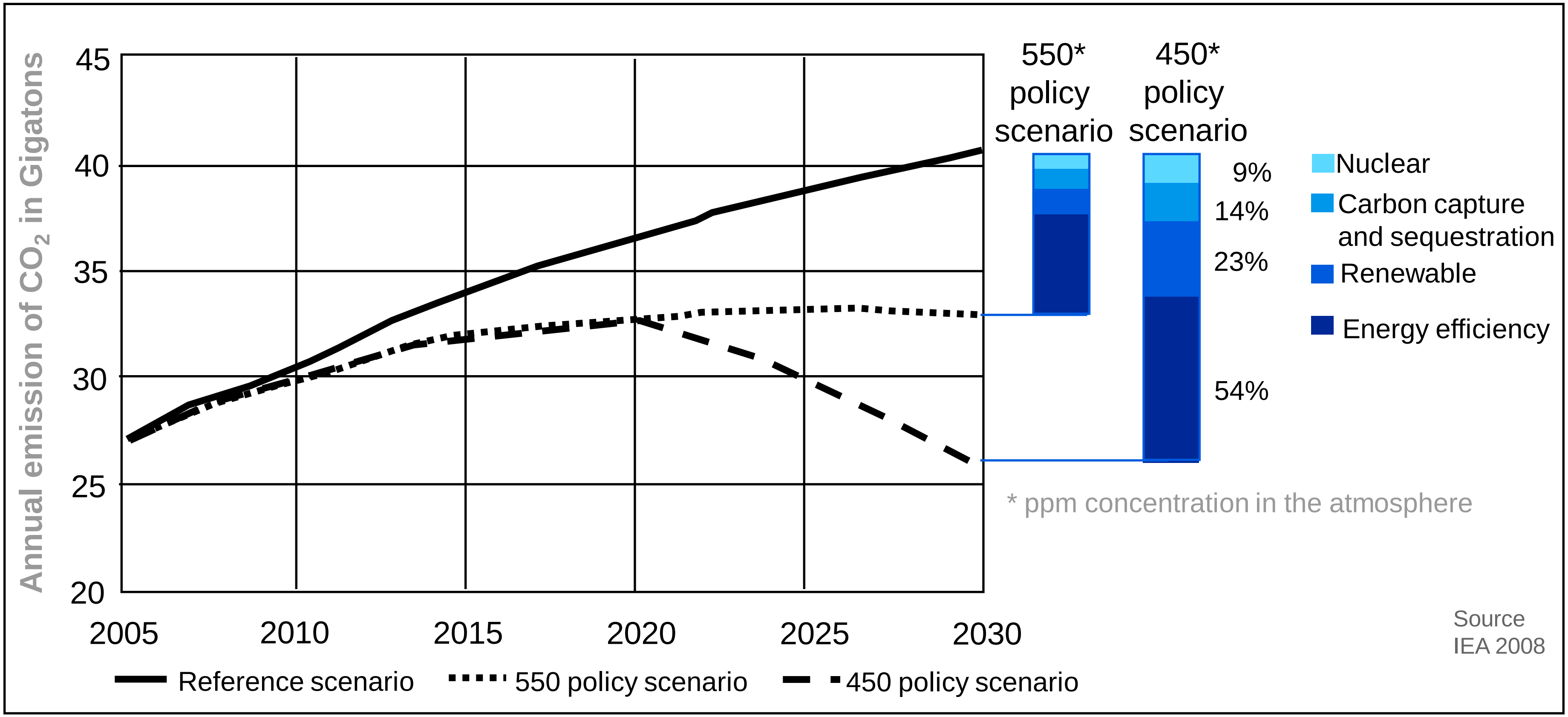
ABB Solar Center of Competence , IRES Workshop. December 16th 2011

Grid Integration of Renewable Energy
Solar systems

Integration of Generation technologies
Renewable integration



Introduction
Drivers and challenges. Mix of generation



Energy efficiency and renewable power generation could provide almost 80 percent of the targeted reduction

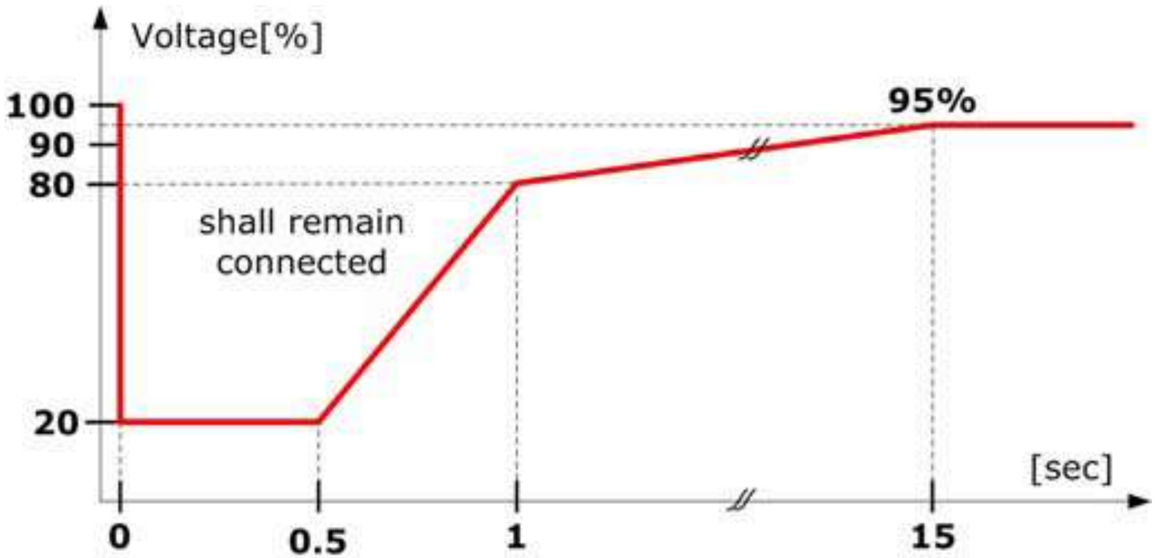
Grid integration of renewable energies
Need for grid requirements

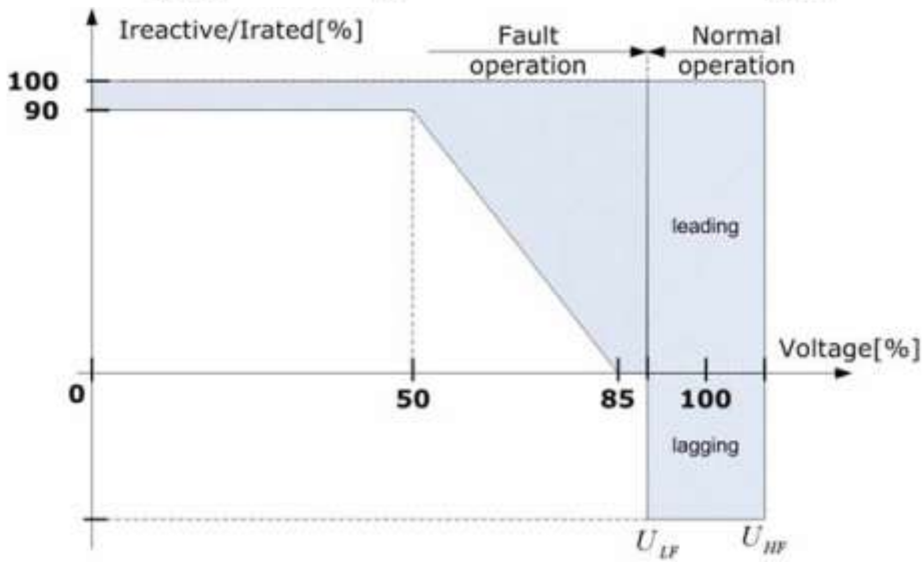
- **TSOs demand for a safe and reliable operation of the grid:**
  - Continuity of supply
  - Quality of supply
  - Spinning reserve and power support during system disturbances

- **Large integration of RES may result in restrictions for grid safety and operation:**
  - Dis-continuity of supply – Generation uncertainty
  - Disconnection during voltage dips – impact on stability
  - Reduced quality of supply (power factor/ harmonics/flickering) – grid distorsion, voltage deviations

- **The increase of Renewable in the generation mix has resulted in the necessity of an updated grid operation code**

Grid integration of renewable energies
Spanish OP12.3 – Low Voltage Ride Through Capability



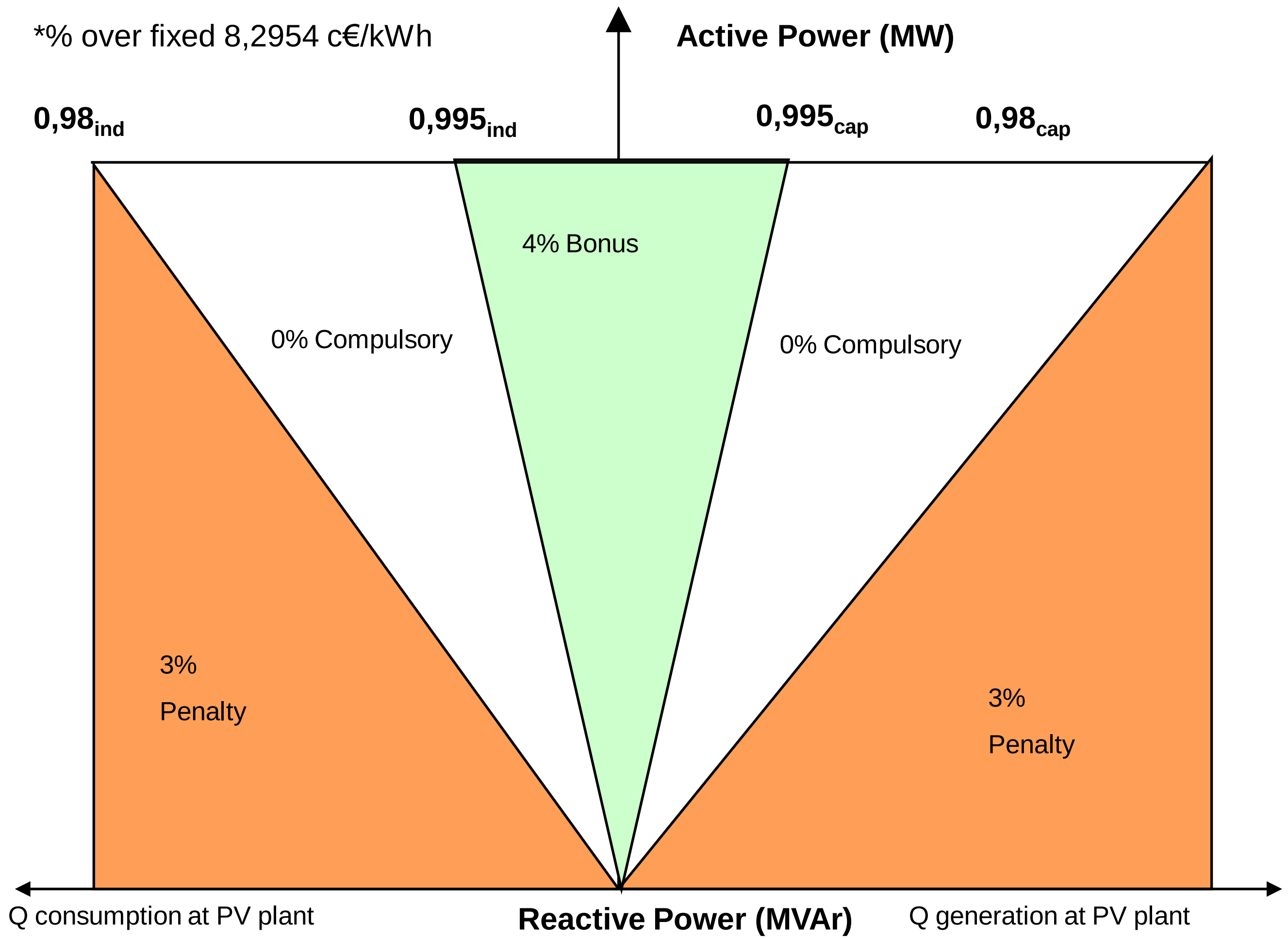


During voltage dips PV plant

Shall remain connected

Must provide maximum Q support to reinforce the grid response

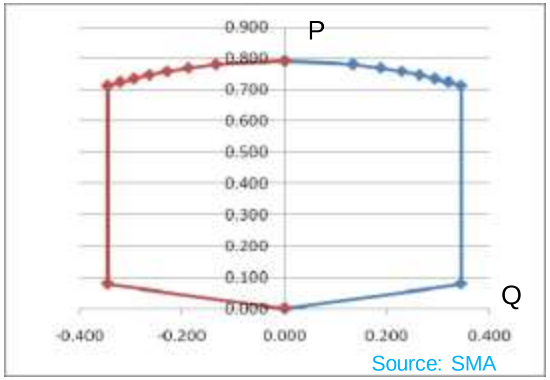
Grid integration of renewable energies
Spanish OP12.3 / RD 1545 – Power factor correction



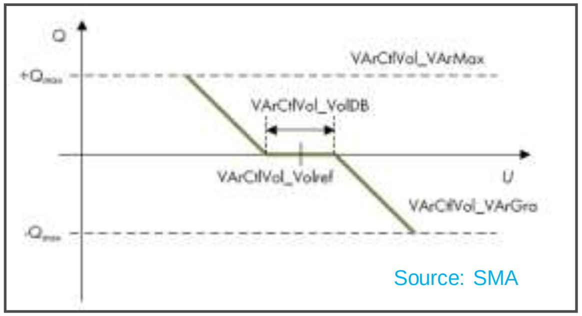
The PV plants should control the Q generation – consumption at the interconnection point

Grid integration of renewable energies
Technical challenges – low voltage ride through (LVRT)

- **Rigid inverters**
  - Low power factor correction capability
  - Disconnection from the grid during low voltage dips
  - Possible Solutions:
    - Change to flexible inverters (LVRT)
    - Retrofit in inverters (software/hardware)
    - FACTS series devices (DVR or similar)
    - Increase power factor capability by installing reactive compensation solutions

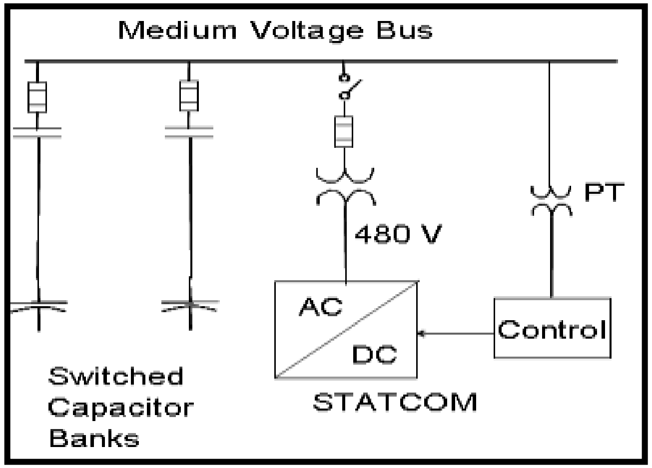


- **Flexible inverters**
  - Provide power generation telecontrol → TSO dispatching
  - Able to withstand voltage dips – minor inverter modifications
  - Capable of providing wide power factor control
  - May demand additional solutions
    - To fulfill power factor restrictions (traditional reactive compensation and/or STATCOM)
    - Dynamic recovery to fulfill grid codes (STATCOM)

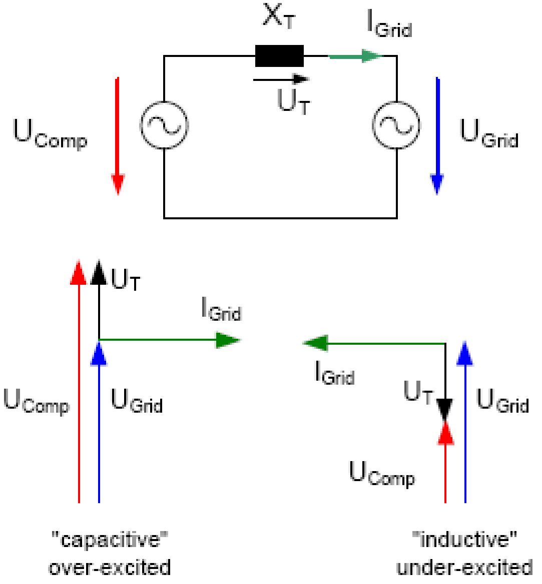


Grid integration of renewable energies
Technical challenges – shunt solutions

- **Switched capacitor banks**
  - Ability to improve the power factor correction
  - Do not contribute dynamically during LV dips
  - Possible solution for
    - PV plants (> 2MW) with flexible inverters
    - PV plants (< 2 MW) with rigid inverters

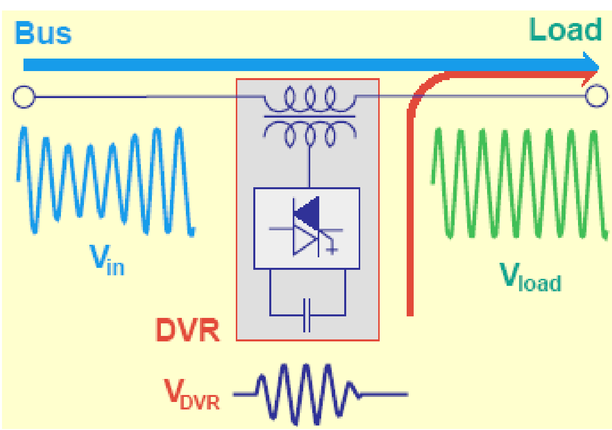


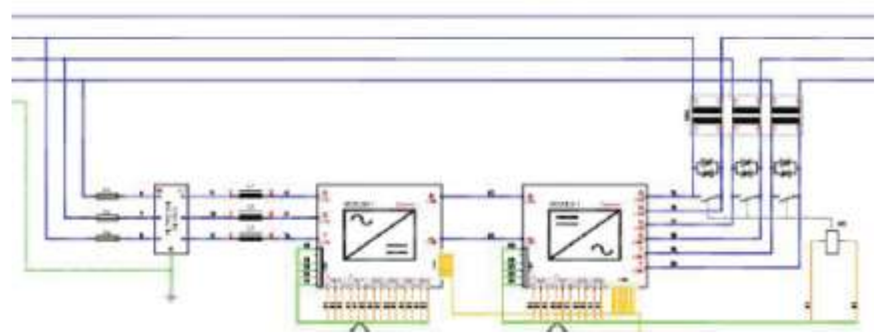
- **Shunt solutions → STATCOM**
  - Based on voltage source converters (VSC PWM)
  - Controlling the V_grid by injecting/absorbing Q
  - Limited capability during LV dips
  - Able to provide
    - Power factor and voltage support
    - Dynamic reactive support after voltage dips to ensure grid code restrictions for Q and voltage restoration



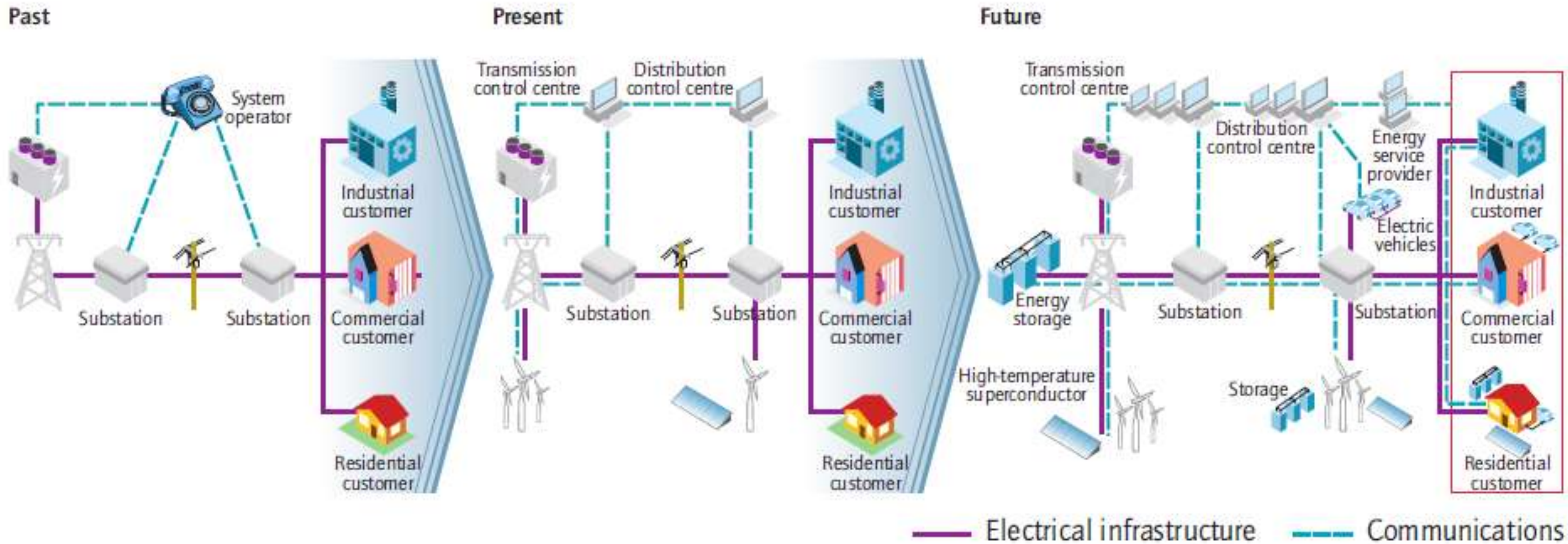
Grid integration of renewable energies
Technical challenges – series solutions

- **Series solutions → DVR (Dynamic Voltage Restorer) or similar**
  - VSC + booster transformer based solution
  - 2 models depending on the energy storage:
    - Capacitor banks (MV)
    - Back to back (LV)
  - Mitigates voltage dips by injecting over-voltages in the system
  - Limited by the Energy storage active power supply capability
  - No reactive power support during voltage dips





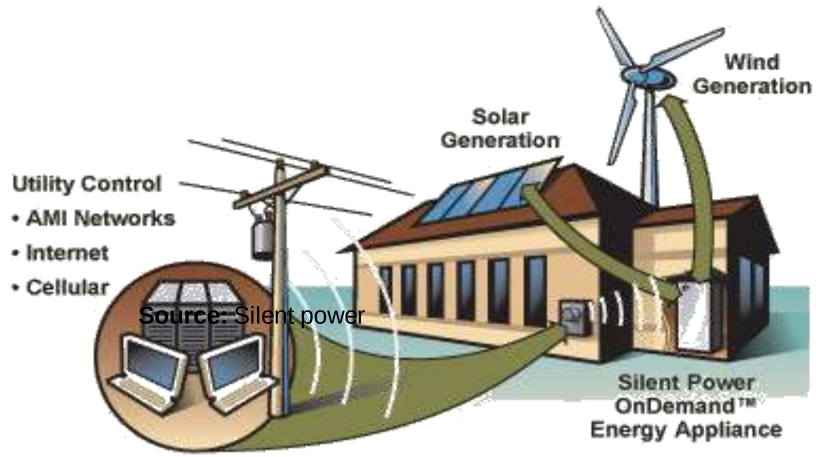
Smart grids in distribution systems
Future electrical systems



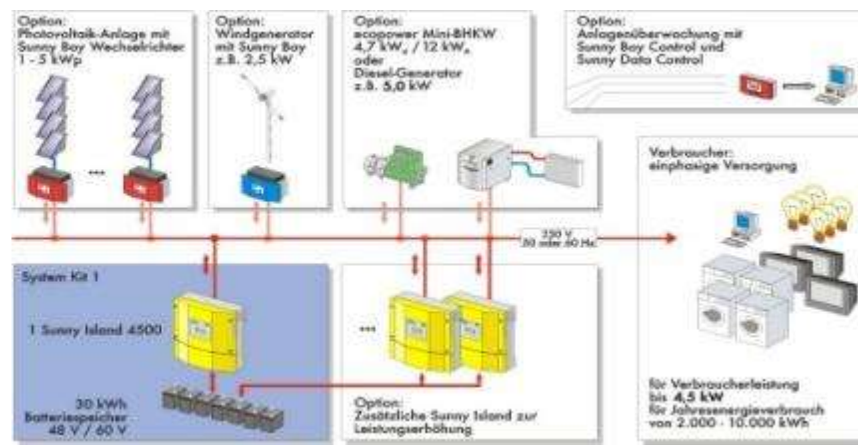
Source: Unless otherwise indicated, all material derives from IEA data and analysis.

Smart grids in distribution systems
Approaches to DG integration - trends

- DG integration interfaces:
  - a) End-user to HAN or building (Home Energy Systems)
  - b) Directly to the utility (DMS)
  - c) Aggregation mechanisms
    - Integration to demand response programmes
    - Virtual Power Plants (VPPs)
    - Microgrids
  - *Modular hybrid systems
    - Addressing intermittency



Source: Silent power



Source: SMA Technologie AG

Smart grids in distribution systems
Technical challenges

traditional power plants

solar plants

wind farms

distributed generation

- **Intermittent generation** for wind and solar
  - Production planning and forecasting to stabilize the grid
  - Load following capability of the EMS
  - Load management in islanded mode
- **Grid automation with DG generation bi-directional flow**
- **DG interaction with storage**
- **DG interaction with HEMS for residential**
- **Control** and **protection** techniques/objectives
- Limiting **frequency fluctuations** and **voltage** dips when sudden load increase occurs
- **Resynchronization** techniques – management of transient periods
- Steady state & **asymmetrical** conditions due to single phase loads
- **Black start** capability
- **Communications**

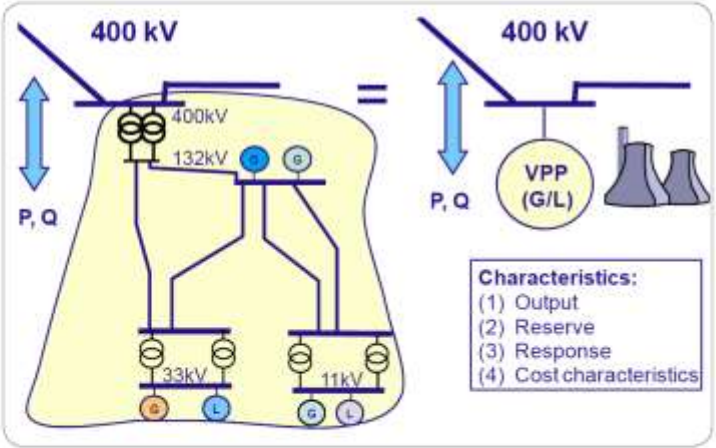
Isolated or Weak Systems
Problems & Solutions

- **Short system inertia**
  - Reduced power installed
  - Imbalance Generation and Consumption
- **Low Stability**
  - Frequency deviation
  - Blackout
- **Bulk centrally located power plants**

- **Distributed Generation**
  - Renewable Energy
- **Power-Frequency control**
  - Virtual Power Plants
- **Energy Storage (ESS)**
  - Flywheel, BESS (Statcom,DynaPQ)
  - Hydroelectric system

Applications of smart grids in distribution systems
Virtual power plants (VPPs)

- **Current situation**
  - Ancillary services provided only by centrally dispatched generation
  - DG is technically capable of providing these services
  - DSO are “blind“ to real-time contribution from DG
- **The concept**
  - Flexible representation of a DER portfolio (generation and loads)
- **Activities**
  - Commercial: Used to interact and trade in wholesale markets
  - Technical: Offer services to SO

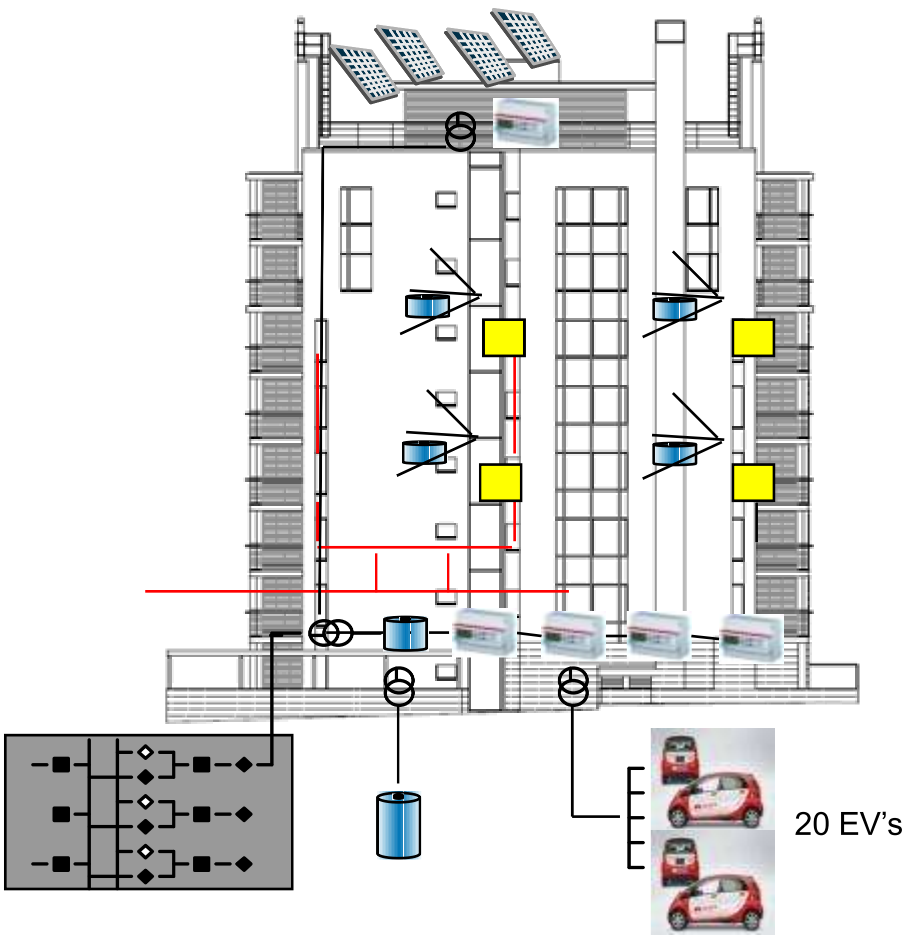


Source: FENIX project, 2009

Applications of smart grids in distribution systems
Microgrids

- Locally controlled cluster of DG, loads and storage
- From the grid perspective, a microgrid grid behaves as a single load/generator
  - Electrically
  - In energy markets
  - Minimise impact to surrounding grid
  - Ease congestion
- Ability to:
  - operate in islanded mode
  - With purchase energy / ancillary services from main grid and potentially selling back excess energy
- Control paradigms
  - Centralised (master/slave)
  - Decentralised
- Main efforts: NAM, EU, Japan

Applications of smart grids in distribution systems
Stockholm Royal seaport – Home energy microgrids



- 1 Building with 40 apartments
- Loads:
  - Aprox 4100 kWh per household/year
  - **Demand response**: dishwasher and textile washing/dryer, Total 43 kWh/daily
- **PV** generation, 10 000 kWh/year (100m2)
- **Battery storage**: 13 kW, 54 kWh recycled daily, approx 1500 kg batteries
- **EV** connection for 20 vehicles

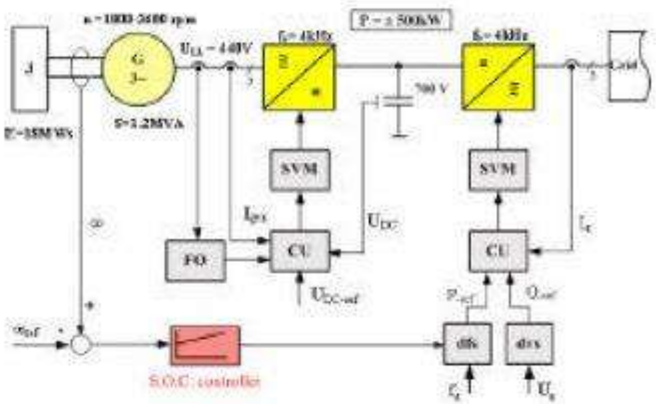
Renewable integration – ABB Experiences
El Hierro - Gorona del Viento – Hybrid System Control

- **Components:**
  - 11,5 MW (5 WTs) Wind generation
  - 11,32 MW (4 HT) Hydro generators
  - 6 MW pumping storage + 11 MW diesel
- ABB Supply:
  - Control design strategy studies
  - Transformers + Drives + motors
  - MV switchgear+ protection
  - Control equipment + Automatic Generation Control

Integration Applications
Flores Island, Azores, Portugal

- **Objective**
  - Maximize integration of Wind and Hydro energy
  - Increase system stability
- **Mix of Diesel, Wind and Hydro generation**
  - Four Diesel generators (2460 kW)
  - Two Wind turbines (630 kW)
  - Four Hydro power generators (1350 kW)
- **Flywheel Energy Storage (18 MW)**
- **Conclusions**
  - Stabilize electric system
  - Fuel saving
  - Minimum diesel generators
  - Increase generators life-time
  - Sustainable development
  - Positive environmental effects

Azores Islands

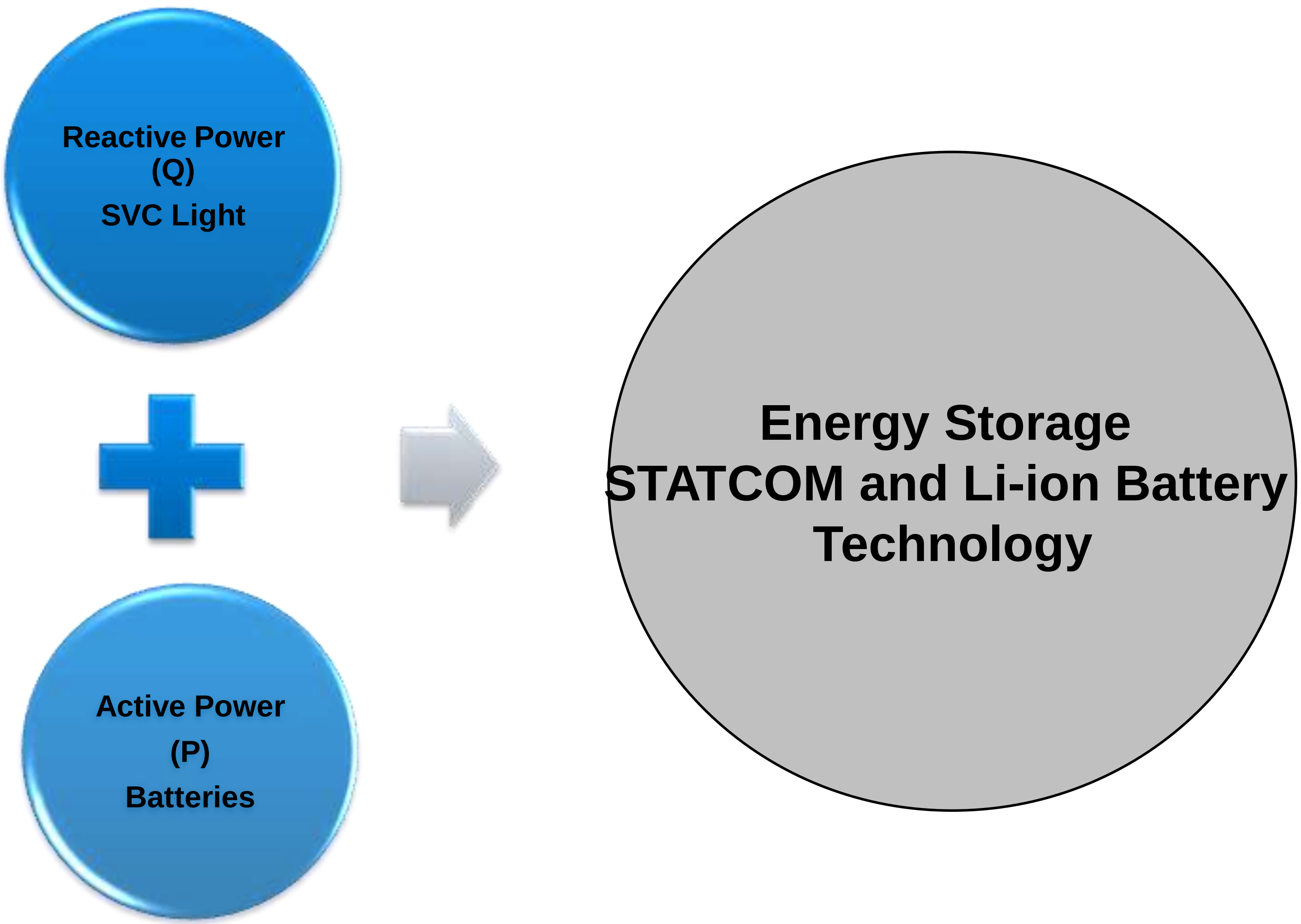


FESS (Flywheel Energy Storage System)

Applications of smart grids in distribution systems
Energy storage based on STATCOM Technology

Segment	Grid Support (substation connected)	Renewable Integration	Distributed Energy Storage
Connection level	T&D S/S >5 kV	> 690 V	230-400 V
Storage size and time	1 – 100 MW 2 – 360 min	500 kW - 100 MW, 30-360 min	25 – 200 kW 30 – 240 min
Main applications	Frequency Regulation, Voltage Support, Investment Deferral, Electric Supply Reserve Capacity, EV Fast Charging	Time-shift, Capacity Firming, Wind Generation, Grid Integration	Energy Cost Management, Demand Charge Management, Power Quality, EV Slow Charging

Applications of smart grids in distribution systems
Energy storage based on STATCOM Technology



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Applications of smart grids in distribution systems
Energy storage based on STATCOM Technology

- **Grid Code compliance**
  - Power factor correction (reactive power) at PCC
  - Flicker mitigation
  - Harmonics
- **Renewable Capacity Firming**
  - Keep renewable production within acceptable forecasted window
  - Compensate for short term intermittency from wind or solar
- **Ramping**
  - Maintain power until alternative power is brought online
  - Avoid power system collapse when renewable are quickly dispatched from network

SVC Light with storage enhances:
  - The network's grid stability, reliability, flexibility and efficiency
  - The allowance of CO2 free generation in the grid

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Slide 78

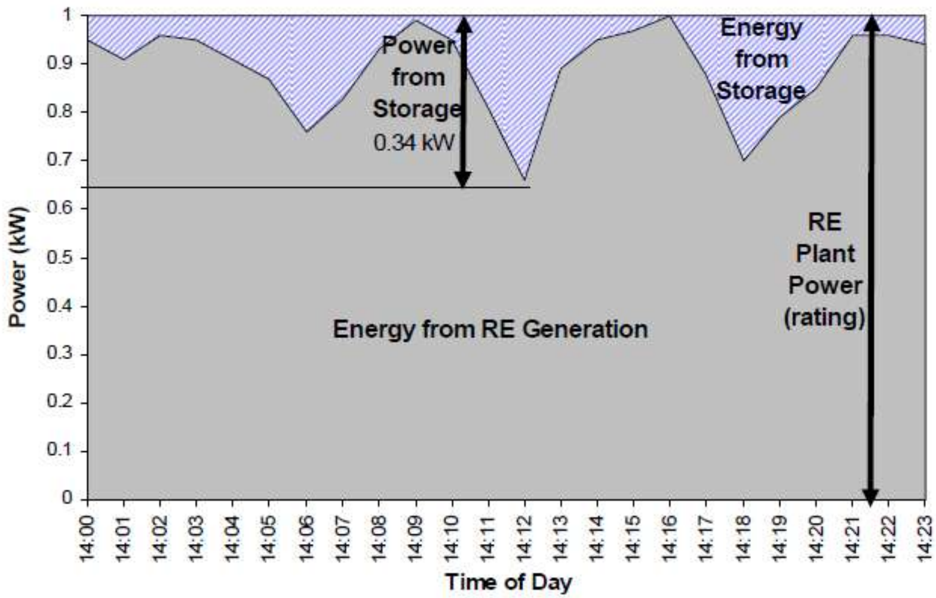
Energy Storage Systems
Why energy storage

- **Efficiency**
  - Environmental restrictions
  - Optimization in the usage of the transmission and distribution grid
- **Reliability and sustainability**
  - Mix of generation: tendency to continue increasing the renewable share (from few MW to several GW)
    - Impact on voltage and frequency stability
    - Intermittency and uncertainty for energy availability
  - Growth of distributed renewable generation (MV and LV levels)
    - Micro-grids
    - Virtual power plants /Isolated Systems stability
- **Capacity**
  - Charging for e-mobility
  - Vehicle to grid

Applications
- Black start
- Frequency regulation
- Renewable energy integration
- Spinning reserve
- Power protection

Key benefits
- Flicker compensation
- Voltage sag correction
- Reactive power control
- Spinning reserve
- Load leveling
- Peak shaving

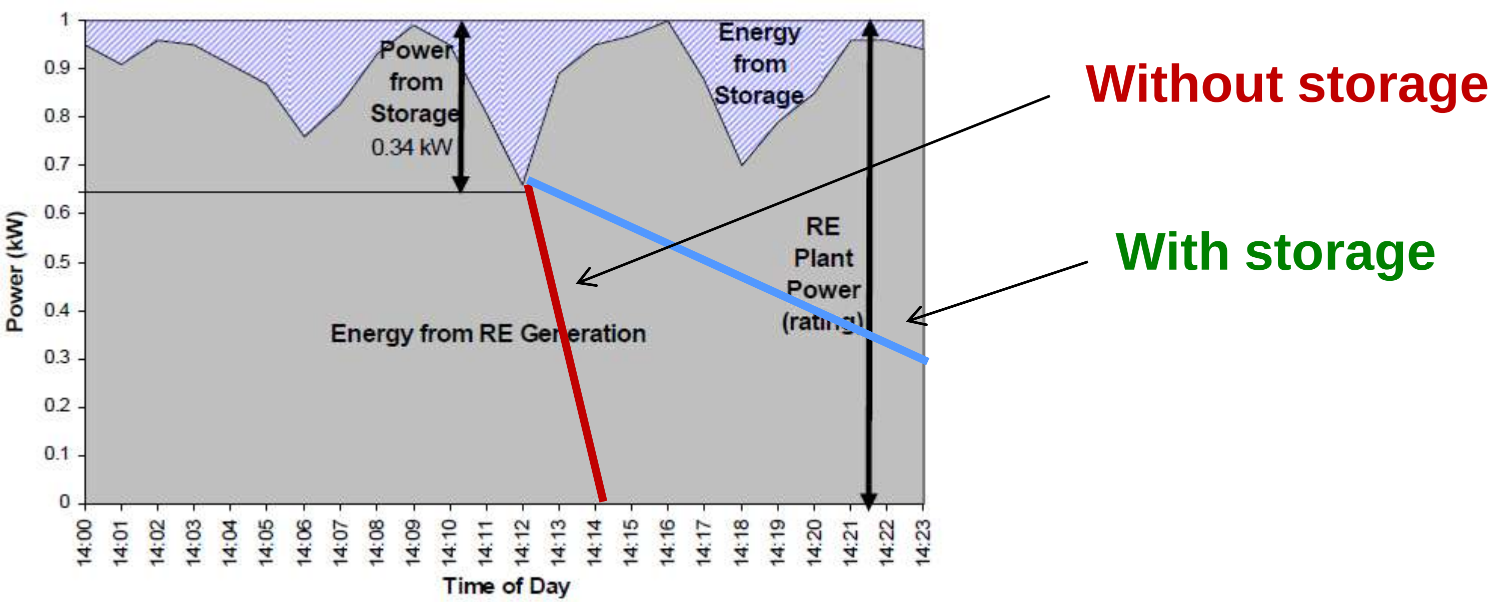
ESS applications
Capacity firming for renewable intermittency



- Short duration intermittency from variations in wind speed and/or shading of the sun occur through out the day
- Objective is to use the solution to “fill in” so that the combined output from the renewable generation plus storage is close to constant
- Maintain higher forecasted levels of generation => higher revenue
- Increased amount of CO_2 free generation to allow renewable integration

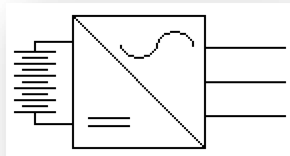
ESS conceptual applications
Ramping. Need for generation dispatch

- Sudden changes in wind – heavy wind conditions could lead to that an entire wind park is disconnected to the grid, which could have severe impact on the power system
- Need for dispatchable power sources whose output can change rapidly => SVC Light with Storage to play a role
- Bridge the time needed to start up other generation



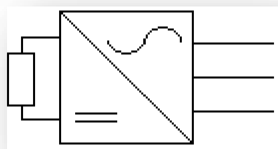
Technology Overview

Battery



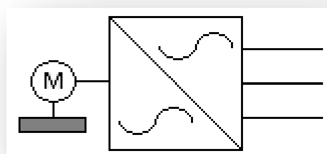
Long & Short Term Energy Storage

Resistive Dump Load



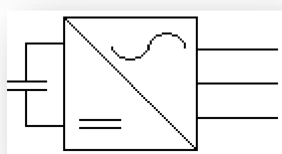
Grid Stabilization

Flywheel



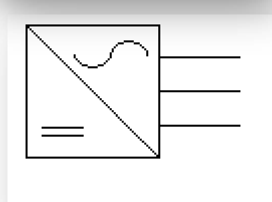
Grid Stabilization & Short Term Energy Storage

Super Capacitors



Grid Stabilization

STATCOM



Grid Stabilization

Grid applications for energy storage
Discharge times

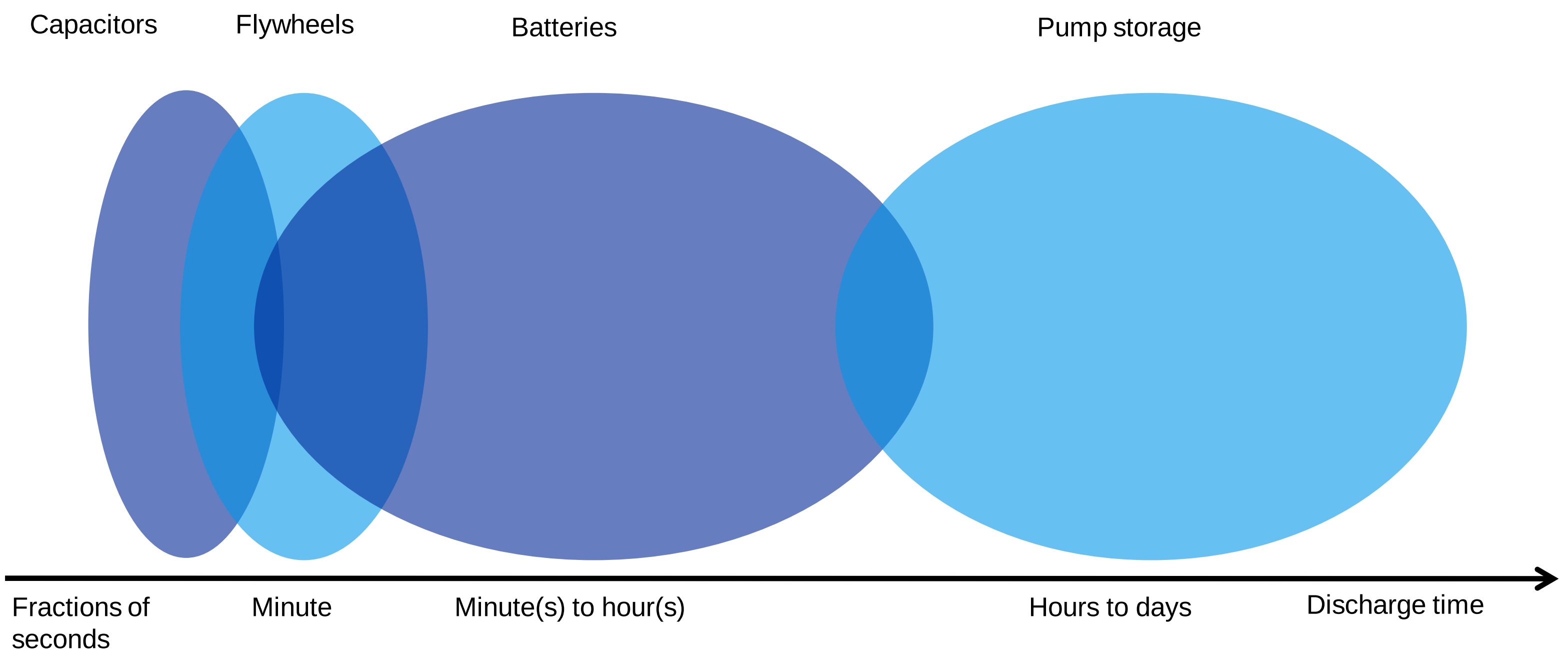


ABB Solutions for grid support
Portfolio

- Steady Voltage Support: Capacitors banks/filters
- Dynamic Voltage support: SVC (SVC Light with VSC tech)
- Energy storage systems: Focus on Active Power
  - Static Systems: Statcom
  - Mechanical Systems: Flywheel
- Grid Stabilization Systems. DynaPeaQ

ABB Solutions for grid support
SVC Light

ABB standard FACTS device

- Top class flicker mitigation
- Active filtering of harmonics
- Compact, small footprint
- Up to 150 MVAR

ABB Solutions for grid support
PCS based STATCOM Solutions

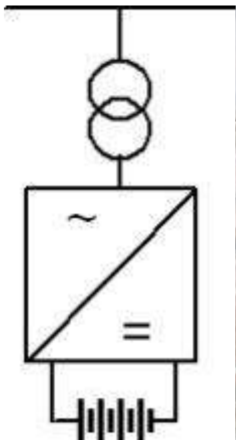
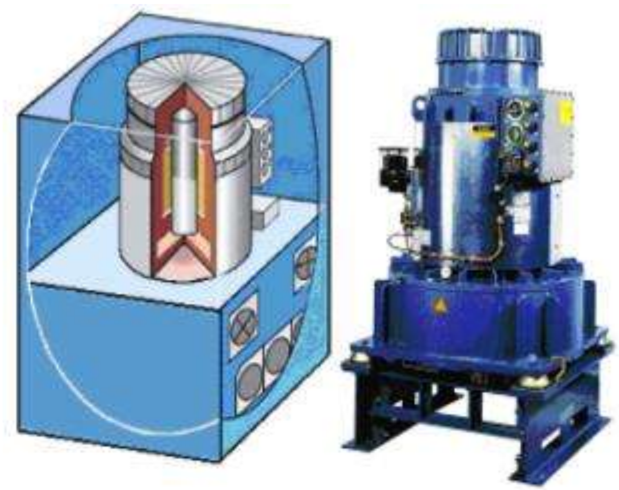
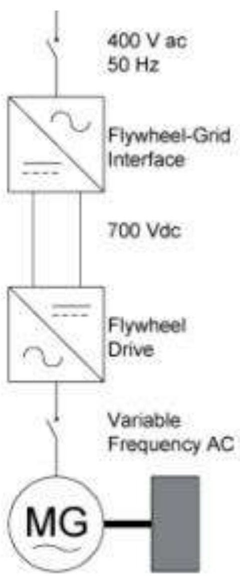


ABB standard FACTS device

- PQ oriented development
- Power conditioner
- Compact, small footprint
- Flexible configuration with diferent energy storage elements (batteries, flywheels)
- Mid range 1- 10 MW storage, modular approach

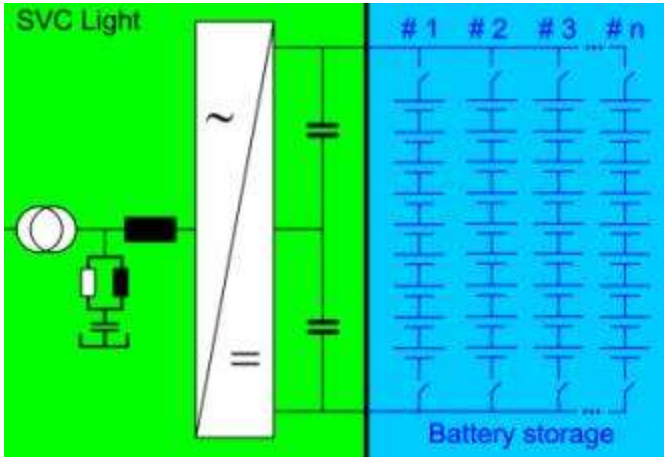
ABB Solutions for grid support
Mechanical Power Storage (FlyWheel, FESS)





- **Flywheel Energy Storage:**
  - Flywheel Spinning Mass
  - AC-DC-AC Converter System
  - Control and SCADA System
- **Advantages:**
  - Stabilizes power system
  - Increase renewable energy penetration
  - Improve quality of supply
  - Response time ≈ 5 ms
  - Fault ride trough
  - Provide real and reactive power

ABB Solutions for grid support
DynaPeaQ solution



Top Class HW

- SVC Light based tech
- Li-ion batteries – 15 years avg life
- Control and SCADA System

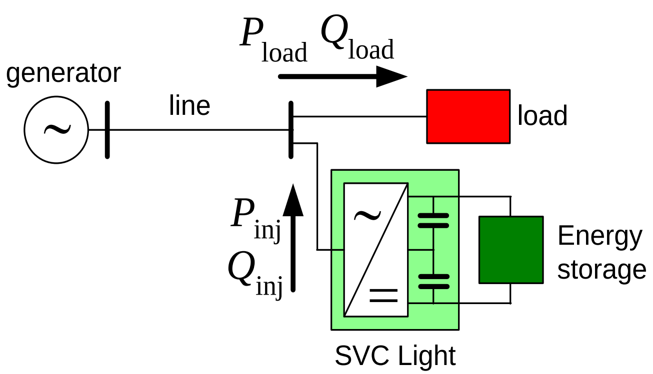
Advantages:

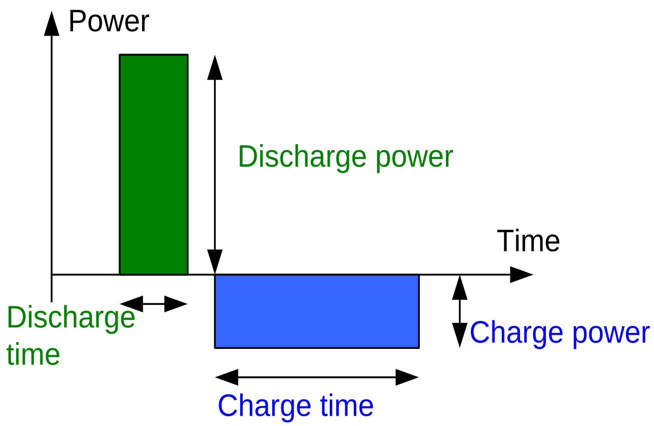
- Large ratings (up to 50 MW storage, 1 hour)
- Standardized building blocks. Scalability
- HV Battery strings (3kV). Higher Efficiency
- Service Ready. Improves RAM
- Provide real and reactive power control, increases voltage stability

Environmental aspects of batteries

- Direct material recycling of 70 %
  Indirect recycling of 30% (energy/cement industry raw material)

DynaPeaQ
Grid interface

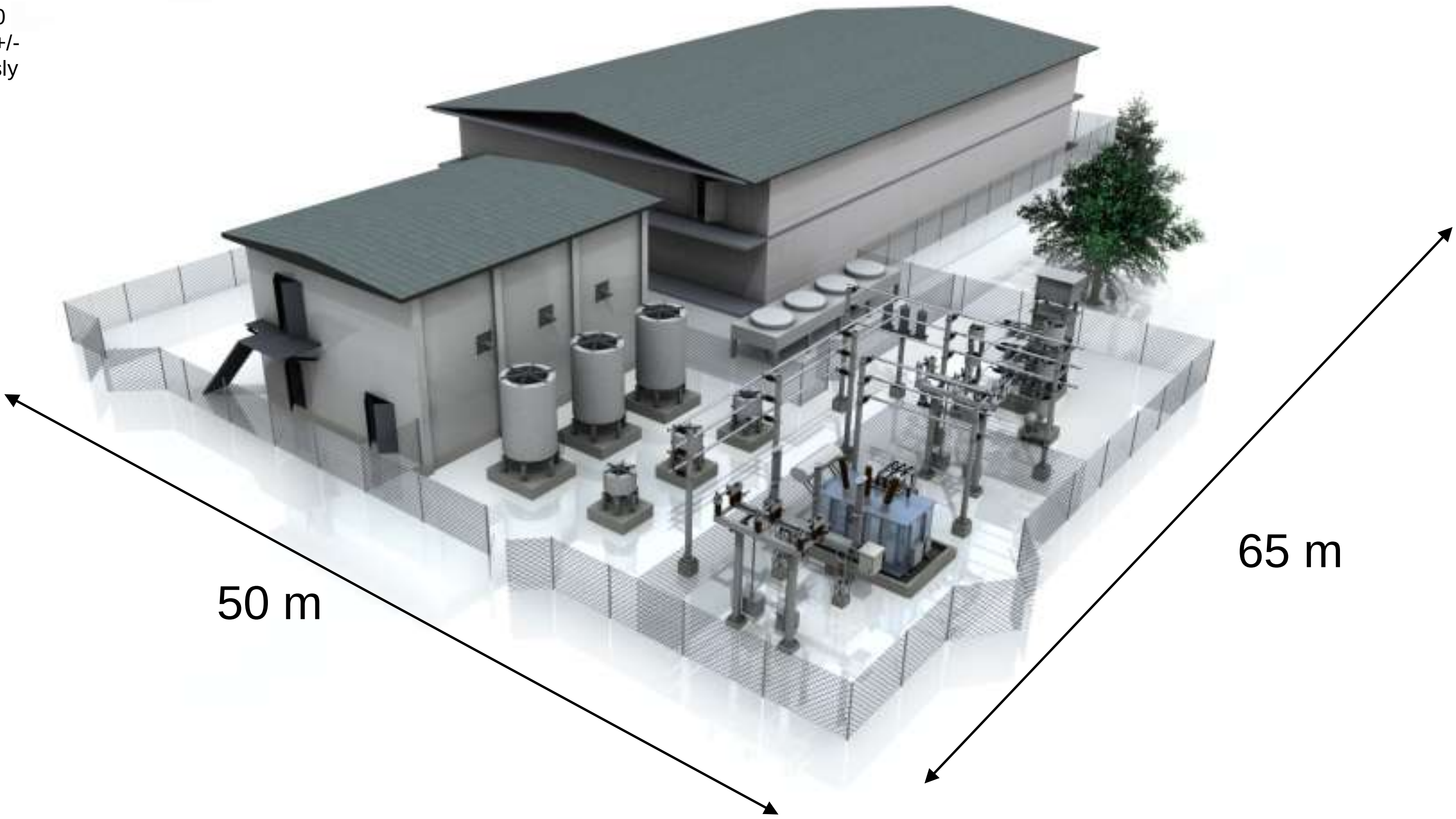




- Energy storage connected to the DC side of ABB SVC Light® (VSC tech)
- Storage size depending on power level and discharge time
- Discharge followed by charge
- Focus on “**dynamic**” properties:
  - Large number of charge and discharge cycles
  - High power during relatively long discharge time
- ABB has selected a high performance battery as storage

DynaPeaQ
Typical layout

Typical layout for 20 MW during 15 min +/- 30 Mvar continuously

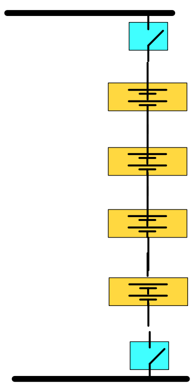


DynaPeaQ
Hierarchy of the battery solution

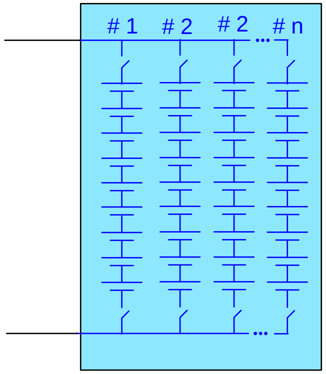
Cell

Module

Room

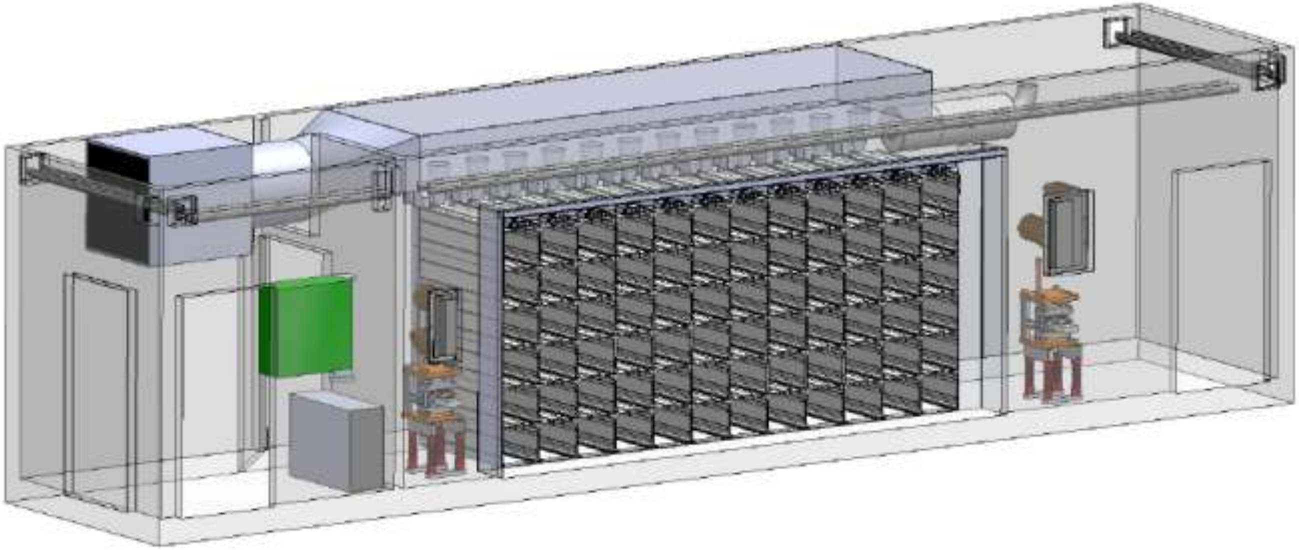


String



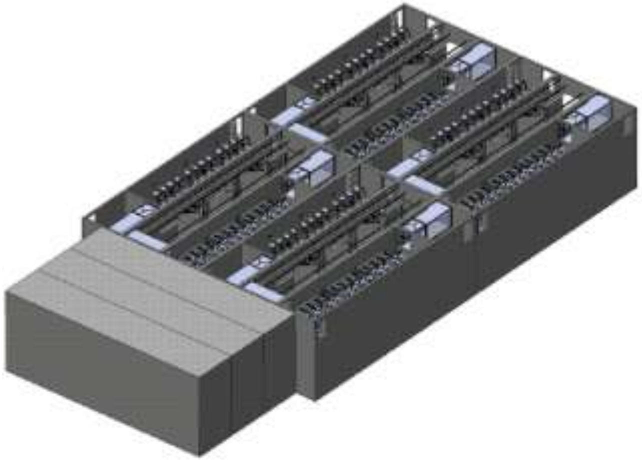
Storage

DynaPeaQ
Battery room



- Standardized building block
- Nominal voltage 3 kV

DynaPeaQ
Series connected battery rooms



- Battery rooms combined with service corridors
- Either containerized or site buildings

Grid applications for energy storage
Backup power

DynaPeaQ continuously supports the grid with reactive power and in case of generation loss DynaPeaQ will push active power into the grid until new generation is available.

Grid applications for energy storage
Intermittent loads of a railway

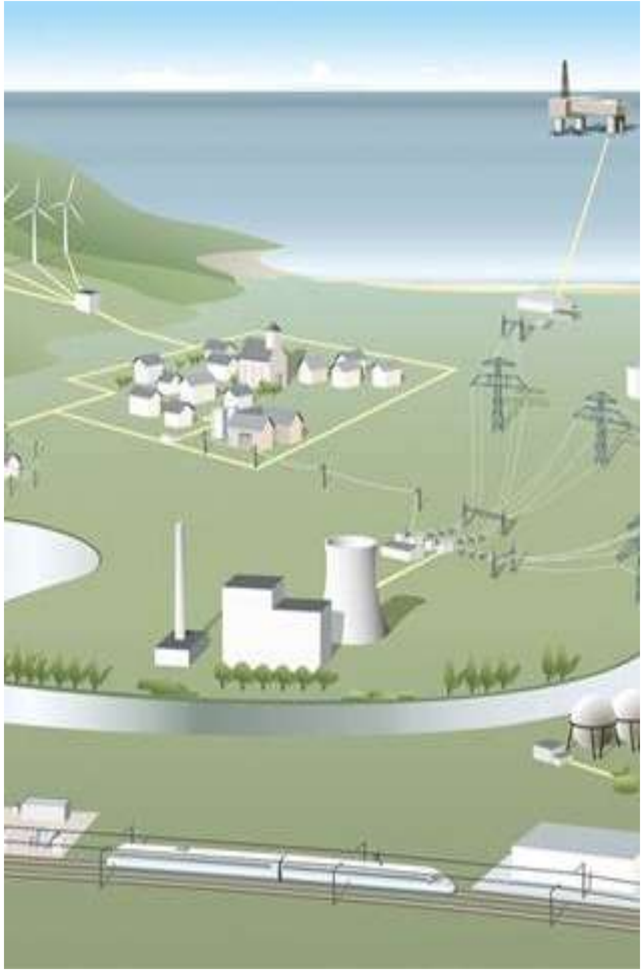
Accelerating a heavy train can expose the grid to a peak load that traditionally gave rise to extensive capacity build out investments. With DynaPeaQ the required acceleration power is literary taken from the train’s latest deceleration.

Grid applications for energy storage
Emergency and short-time power

In a distribution grid a compensator for reactive power would typically provide for power quality improvement. The energy storage adds a whole range of new functions.

- In cases where local loading exceeds grid capacity DynaPeaQ provides load support
- After black-out restoration, the Energy Storage might be the starting point
- For sensitive loads, the Energy Storage can provide overbridging power between outage and backup power

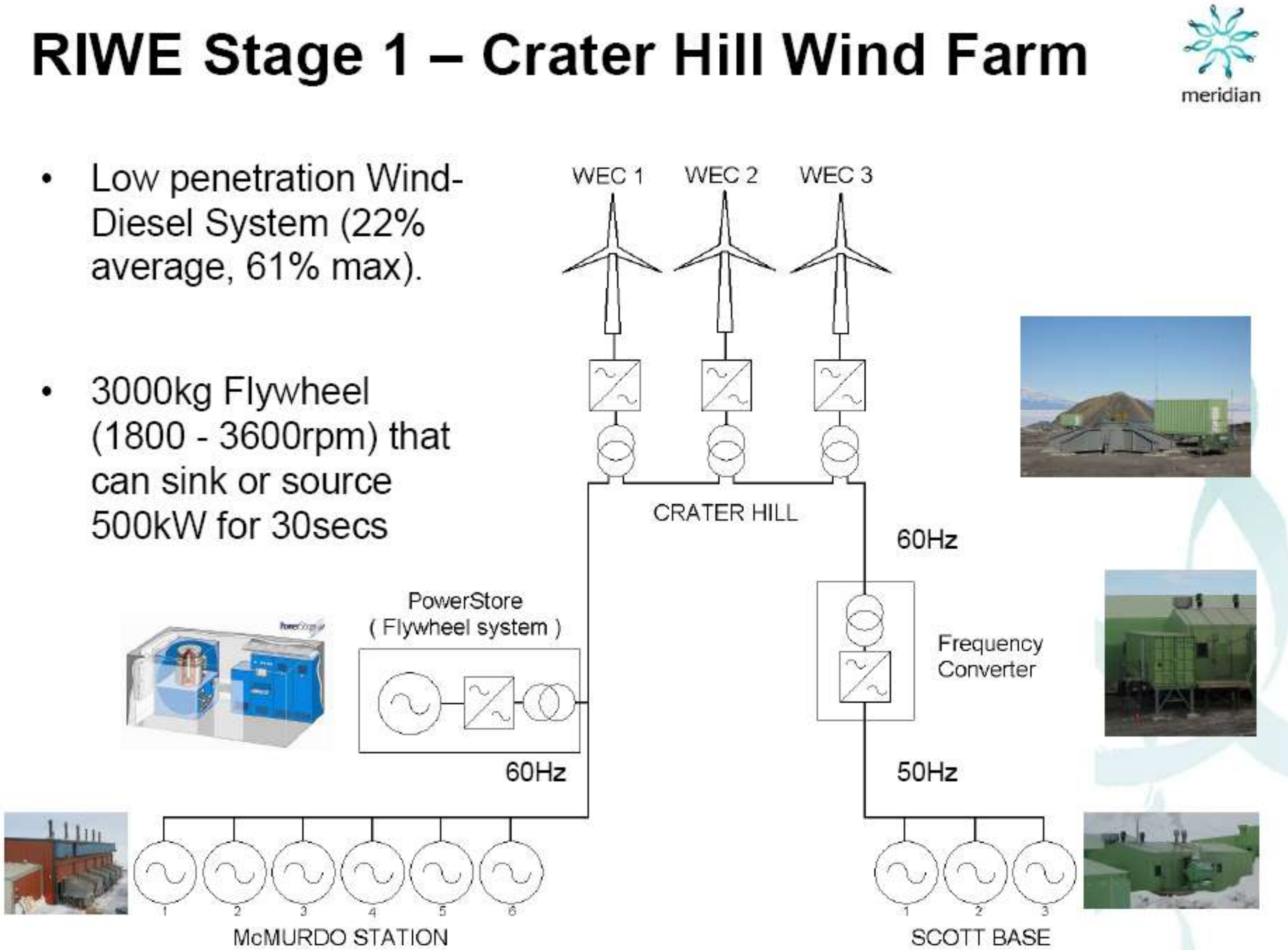
Grid applications for energy storage
Smart Grid



Smart Grid applications with DynaPeaQ:

- Provides possibilities for connection of renewables
- Dynamic energy storage
- Integration of electric vehicles
- Peak-load shaving
- Ancillary services

Ross Island, Antarctica



• Stage 2 plans are to increase the number of wind turbines, creating a high penetration system

Marble Bar, Australia

Marble Bar Solar/Diesel power station, Western Australia

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