European Association for Storage of Energy

TVAC WG1

Storage Efficiency Calculation Methods

Content

1. General

Table 1 Segmentation of storage in time

Segment	Description	Discharge duration
1)	Power system fast acting storage	< 15 min
1a)	Power quality	< 1 min
1b)	Power system stability	≥ 1 min, <15 min
2)	Power storage	< 1 h
3)	Energy storage	≥ 1 h
3a)	Daily storage	< 24 h (commonly 6 h)
3b)	Weekly storage	< 168h (commonly 30–40h)
3c)	Monthly Storage	< 720h
3d)	Seasonal storage	≥ 720 h

General efficiencies electric components

Table 2 Overview of general electric component efficiencies

Component	Efficiencies	
	Lower range (small power) [%]	Upper range (high power) [%]
E-motor (medium voltage)	94,5	97
E-motor (low voltage)	85	97
E-motor (direct current)	93	96
Inverter/rectifier	85	95
Generator	98,5	99
Transformer	98,5	99
Electrical AC heater	97	99,5
Air separation unit (ASU)	0,6 kWh/Nm³	0,3 kWh/Nm³
Air liquefaction unit with cold recycle	0,6 kWh/Nm³	0,2 kWh/Nm³

Nomenclature

Table 3 Variables

Symbol	Definition	Unit
A	Surface area	m²
c_p	Specific thermal capacity	kJ/(kgK)
E	Energy	kJ

Symbol	Definition	Unit
F	Faraday constant	C/mol
H	Height/Head	m
i	Specific energy	kJ/kg
IC	Internal consumption	kJ
k	Coefficient of heat transmission	$W/(m^2K)$
LHV	Lower heating value	kJ/kg or kJ/Nm^3
m	Mass	kg
$\dot{m}$	Mass flow	kg/s
n_V	Volumetric amount of substance	mol/Nm^3
P	Power	kW
Q	Thermal energy	kJ
$\dot{Q}$	Thermal power	kW
R	Thermal resistance	K/W
r	Radius	m
s	thickness	m
T	Temperature	K
t	Time	s
U	Voltage	V
W	Specific energy consumption	kJ/kg or kJ/Nm^3
$x_{C,D}$	Time-factor	–
z	Charge number (valence)	–
α	Heat transfer coefficient	$W/(m^2K)$
ε	Emission ratio	–
η	Efficiency	%
λ	Thermal conductivity	W/(mK)
ρ	Density	kg/m^3
σ	Stefan-Boltzmann constant	$W/(m^2K^4)$
Φ	Porosity	–

Table 4 Indices

Symbol	Definition	Unit
0	Initial conditions	–
AC	Alternating current	–
ad	Adiabatic	–
amb	Ambient	–
An	Anode	–
B	Bubble formation	–
b	Bed	–
Br	Brick	–
C	Charge	–

Symbol	Definition	Unit
Ca	Cathode	–
Cap	Capacitor	–
CH4	Methane	–
CO2	Carbon dioxide (-separation)	–
compr	Compressor	–
D	Discharge	–
Dia	Diaphragm	–
E	Ohmic losses	–
el	Electric	–
F	Fuel	–
g	Gross	–
Gen	Generator	–
h	Hydraulic	–
H2	Hydrogen	–
HEHR	Heat exchanger heat recovery	–
HR	Heat recovery	–
HRSG	Heat recovery steam generator	–
HT	High temperature	–
HTF	Heat transfer fluid	–
I	Inverter	–
in	Inlet	–
KOH	Potassium hydroxide	–
m	Mechanical	–
M	Motor	–
NG	Natural gas (as fuel)	–
P	Pump	–
PB	Packed bed	–
R	Residual	–
rev	Reversible	–
RT	Round-trip	–
s	Stored	–
st	Storage time	–
T	Turbine	–
th	Thermal	–
Tr	Transformer	–

2. Thermal storage systems

Heat (hot water/PCM)

Additional losses during storage:

- $\eta_{storage}$ (thermal loss = time dependent factor)

Non-linear, unsteady process

- efficiency loss is dependent on the following factors:
  - time duration storage
  - installation location
  - storage capacity
  - temperature storage medium
  - insulation material

The temperature of the storage medium can be defined as a function of time:

$$T = f(t)$$

Thermal loss = thermal conduction + thermal radiation

$$\dot{Q}_{thermal\ loss} = k \cdot A \cdot \Delta T + \varepsilon \cdot \sigma \cdot A \cdot \left(T^4 - {T_{amb}}^4\right)$$

$$\Delta T = T - T_{amb}$$

$$k = \frac{1}{A \cdot R_{total}};\ R_{total} = \sum R_i\,;\ R_{\alpha,i} = \frac{1}{A_i \cdot \alpha_i};$$

$$R_{\lambda,i} = \frac{1}{2 \cdot \pi \cdot H \cdot \lambda_i} \cdot ln\left(\frac{r_{outside}}{r_{inside}}\right)\ \text{(tube)};$$

$$R_{\lambda,i} = \frac{s_i}{A_i \cdot \lambda_i}\ \text{(plane wall)};$$

$$\dot{Q}_{thermal\ loss} = \frac{\Delta T}{R_{total}} + \varepsilon \cdot \sigma \cdot A \cdot \left(T^4 - {T_{amb}}^4\right)$$

$$\eta_{storage} = \frac{Q_s - \int_0^t \dot{Q}_{thermal\ loss} dt}{Q_s}$$

Efficiency losses during the discharging process due to the following components:

- pump

- heat exchanger heat recovery (HEHR)

Overall efficiency from electric energy to the heat recovery:

$$\eta_{overall} = \frac{E_{th,released}}{E_{el,in}} = \eta_{Tr} \cdot \eta_{el\ heater} \cdot \eta_{storage} \cdot \eta_P \cdot \eta_{HEHR}$$

Source: [POLIFKE2009]

Packed bed heat storage

Efficiency of the packed bed high temperature storage during the thermal charging process:

$$\eta_{C,PB} = \frac{E_s}{E_{in}} = \frac{\rho \cdot (1-\Phi) \cdot A \cdot \int_{x=0}^{x=H} (i_{bx} - i_0) dx}{\int_{t=0}^{t} \dot{m}_{HTF} \cdot c_{P,HTF} \cdot (T_{HTF} - T_o) dt}$$

E_s	energy stored
E_{in}	thermal energy supplied by the heat transfer fluid (HTF, e.g. air) at the inlet of the bed
ρ	solid density of the packed bed material
Φ	porosity of the packed bed
A	cross section of the bed
$i_{bx} - i_0 = \int_{T_0}^{T_{bx}} c_p dT$	specific energy stored in the bed
T_0	initial bed temperature

Efficiency of the packed bed high temperature storage during the discharging process:

$$\eta_{D,PB} = \frac{E_D}{E_{D,max}} = \frac{\rho \cdot (1-\Phi) \cdot A \cdot \int_{x=0}^{x=H} (i_{bmax} - i_x) dx}{\rho \cdot (1-\Phi) \cdot A \cdot \int_{x=0}^{x=H} (i_{max} - i_{end}) dx} = \frac{\int_{x=0}^{x=H} \int_{T_{bx}}^{T_{bmax}} c_p dT dx}{\int_{x=0}^{x=H} \int_{T_{end}}^{T_{max}} c_p dT dx}$$

E_D	energy obtained during discharging period up to time t
$E_{D,max}$	maximum available energy at discharge
T_{bx}	bed temperature at height x and time t
T_{bmax}	maximum bed temperature achieved at the end of charging process
T_{end}	temperature of the bed at the end of the discharging process

Resulting efficiency of the packed bed (PB) high temperature (HT) heat storage:

$$\eta_{PB,HT\ heat\ storage} = \eta_{C,PB} \cdot \eta_{D,PB}$$

Efficiency losses during the charging process due to the following components:

- fan (I)

Resulting charge efficiency:

$$\eta_C = \eta_{Tr} \cdot \eta_{el\ heater} \cdot \eta_{fan(I)} \cdot \eta_{C,PB}$$

Efficiency losses during the discharging process due to the following components:

- fan (II)
- heat recovery steam generator (HRSG)

Resulting discharge efficiency:

$$\eta_D = \eta_{fan(II)} \cdot \eta_{HRSG} \cdot \eta_{D,PB}$$

Additional losses during storage: $\eta_{storage}$ (thermal loss = time dependent factor)

Non-linear, unsteady process

Formula: see above section "Heat (hot water/PCM)"

Overall efficiency energy storage and heat recovery:

$$\eta_{overall} = \frac{E_{th,released}}{E_{el,in}} = \eta_C \cdot \eta_D \cdot \eta_{storage}$$

Source: [IZQUIERDO2013]

Smart electrical thermal storage

Efficiency charging

Total system (single room with electric storage heater)

$\eta_C = 100\ \%$

System electric storage heater

$$\eta_C = \frac{E_s}{E_{input}} = \frac{m_{Br} \cdot c_{p,Br} \cdot (T_C - T_{R,C})}{P_{el} \cdot t_C}$$

m_{Br} total mass of bricks

$c_{p,Br}$ specific heat capacity of bricks

T_C temperature of bricks after charging period

$T_{R,C}$ residual temperature of bricks before charging

P_{el} power electric

t_C charging time

<u>Efficiency discharging</u>

Total System (single room with electric storage heater)

$\eta_D = 100\ \%$

System electric storage heater

$$\eta_D = \frac{E_{output}}{E_s} = \frac{m_{Br} \cdot c_{p,Br} \cdot (T_D - T_{R,D})}{m_{Br} \cdot c_{p,Br} \cdot (T_C - T_{R,C})} = \frac{(T_D - T_{R,D})}{(T_C - T_{R,C})}$$

m_{Br} total mass of bricks

$c_{p,Br}$ specific heat capacity of bricks

T_D temperature of bricks before discharging

$T_{R,D}$ residual temperature of bricks after discharging

T_C temperature of bricks after charging period

$T_{R,C}$ residual temperature of bricks before charging

3. Electrochemical energy storage systems

Acronyms and definitions

- EESS = Electrochemical energy storage system

EESS includes the storage device (battery) with its management systems and any power conversion systems and auxiliary support system, needed to run the system, such as heating or cooling, installed with the storage device. The EESS is connected to the grid trough only one main electrical connection and energy measurements of this document are referred at the point of connection.

Please refer to the block schematic:

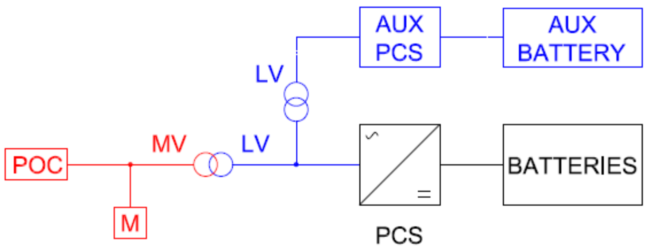

Figure 1 Block schematic of the grid connection of an EESS.

POC point of connection

M meter

MV medium voltage (in red)

LV low voltage (in blue)

PCS power conversion system

- Auxiliary support system
  Group of interconnected and interactive parts that perform an essential task as component of an EESS. Such systems are for example cooling and heating devices, circulation pumps, exhaust gas abatement, fire extinguisher, safety barriers and similar facilities.

- Ampere-hour (Ah)
  A quantity of energy obtained by integrating the current in Ampere with respect to time in hours: Battery capacity is expressed in Ah.

- SOC = State of charge
  Amount of stored charge or energy (in Ah or Wh) related to the rated capacity or energy content, typically expressed as a percentage.

- MCL = Max cycle level
  Maximum SOC level (i.e. 100 % of usable capacity) or maximum voltage conditions in accordance with the system manufacturer's specifications.

- mCL = Min cycle level
  Minimum SOC level (i.e. 0 % of usable capacity) or minimum voltage conditions in accordance with the system manufacturer's specifications.

- DOD = Deep of discharge
  Amount of capacity or energy discharged, expressed in per cent, and related to the rated capacity or energy content of the battery.

- Complete discharge/charge cycle
  Cycle where EESS is charging and then discharging (or vice versa) and the difference between the SOC of the EESS at the beginning of the cycle and the SOC of the EESS at the end of the cycle is equal to zero.

<u>EESS round-trip efficiency</u>

The energy output (energy released) from the EESS divided by the energy input into the EESS (energy absorbed) during a complete discharge/charge cycle, expressed as a percentage and including all system losses as well as any electrochemical, electromechanical, or electrical inefficiency involved in the storage of the energy under normal operating conditions, such as heating or cooling (auxiliary consumption).

$$\eta_{AC,RT} = \frac{E_{released}}{E_{absorbed}} = \frac{\int_{MCL}^{mCL} P_{AC}}{\int_{mCL}^{MCL} P_{AC}}$$

Test Routine

a) The EESS shall be discharged to its minimum state of charge level in accordance with the system manufacturer's specifications and operating instructions. The test shall be carried out at 25 °C ambient air temperature external and in immediately close to EESS.

b) The EESS shall be charged at its nominal power (declared by the manufacturer) to full state of charge (100 % SOC or maximum voltage conditions in accordance with the system manufacturer's specifications). The AC energy input $E_{absorbed}$ into the system during charging phase, including all thermal and parasitic losses, shall be calculated as the integration of the AC power value P_{AC}, measured and recorded at regular intervals of time.

c) The system shall be left in standby state for time that will be defined by manufacturer.

d) The EESS shall be discharged at its nominal power (declared by the manufacturer) to its minimum state of charge level (0 % SOC or minimum voltage conditions in accordance with the system manufacturer's specifications). The AC energy output $E_{released}$ from the system during discharging phase, including all thermal and parasitic losses, shall be calculated as the integration of the AC power value P_{AC}, measured and recorded at regular intervals of time.

e) The system shall be left in standby state for time that will be defined by manufacturer.

f) Steps b) to e) can be repeated several times between one (1) and five (5) times, and each time the AC round-trip efficiency value $\eta_{AC,RT}$ has to be calculated as the ratio between energy released $E_{released}$ and energy absorbed $E_{absorbed}$ during, respectively, step b) and step e).

g) The reference performance test values shall be calculated as the mean of the five AC round-trip efficiency values as measured in step f) and resulting by all performed tests, with the standard deviation also calculated and reported.

h) The system shall be recharged in accordance with step b) and the system left in a fully charged state.

4. Chemical storage systems

Hydrogen

- production by electrolysis (alkaline)
- efficiency (based on the production of 1 Nm^3 H_2):

$$\eta_{H2} = \frac{LHV_{H2}}{W} = \frac{LHV_{H2}}{z \cdot n_V \cdot F \cdot U_{Cell}} = \frac{LHV_{H2}}{2392{,}98 \frac{\mathrm{A\,h}}{m_N{}^3\,\mathrm{H_2}} \cdot U_{Cell}}$$

$$U_{Cell} = U_{Cell,rev} + U_{E,Ca} + U_{B,Ca} + \eta_{Ca} + U_{KOH,Ca} + U_{Dia} + U_{E,An} + U_{B,An} + \eta_{An} + U_{KOH,An}$$

- $U_{E,Ca}$ / $U_{E,An}$ ohmic losses in the cathode / anode
- $U_{B,Ca}$ / $U_{B,An}$ bubble formation between the cathode / anode and the diaphragm
- η_{Ca} / η_{An} overvoltage on the surface of the electrode of the cathode / anode
- $U_{KOH,Ca}$ / $U_{KOH,An}$ voltage drop in the electrolyte (KOH) at the cathode / anode
- U_{Dia} ohmic losses of the diaphragm
- Process chain: production → storage of gaseous Hydrogen (e.g. in salt caverns) or injection into the natural gas (NG) grid

$$\eta_{overall} = \frac{E_{th,released}}{E_{el,in}} = \eta_{Tr} \cdot \eta_I \cdot \eta_{H2} \cdot \eta_{compr} \cdot \eta_{storage}$$

- Possible benefit: usage of oxygen → e.g. for Oxy-fuel combustion in a fossil fuel power plant the air separation unit (ASU) is not needed (energy consumption of the ASU: 0,3 - 0,6 kWh/ Nm^3 O_2)

Synthetic natural gas

- Long term storage → e.g. injecting the synthetic natural gas (SNG) into the NG grid
- Producing the hydrogen by electrolysis
- Catalytic methanation of pure CO_2 and H_2
- Process chain: production → storage (natural gas grid)

$$\eta_{overall} = \eta_{Tr} \cdot \eta_{I} \cdot \eta_{H2} \cdot \eta_{CH4} \cdot \eta_{compr} \cdot \eta_{storage}$$

with

$$\eta_{CH4} = \frac{\dot{m}_{CH4} \cdot LHV_{CH4}}{\dot{m}_{H2} \cdot LHV_{H2} + IC_{CO2} + IC_{CH4} - Q_{HR,Methanation}}$$

- η_{CH4} coefficient of performance of methanation (no “efficiency”)
- IC internal consumption
- IC_{CO2} efficiency loss due to effort of CO_2 separation:
  - separation of CO_2 from biomass plant or fossil fuel power plant
  - electrical internal consumption and additional thermal effort to separate CO_2 from an industrial process
- $Q_{HR,Methanation}$ Heat recovery during methanation
- $\eta_{overall} \approx 56\,\%$

Sources: [DBI2012, BAYER2000]

5. Electrical storage systems

Capacitors

Round-trip efficiency

$$\eta_{AC,RT} = \frac{E_{released}}{E_{absorbed}} = \frac{\int_{MCL}^{mCL} P_{AC}}{\int_{mCL}^{MCL} P_{AC}}$$

For explanations see chapter 3. Electrochemical energy storage systems.

6. Mechanical storage systems

Adiabatic compressed air (ACAES)

Same formula as for diabatic system but with the fuel use set to zero.

Diabatic compressed air (CAES)

Round-trip efficiency:

$$\eta_{RT} = \frac{E_{el,released}}{E_{el,in} + E_{th,in}} = \frac{\eta_{Tr} \cdot \eta_{Gen} \cdot P_{m,T}}{x_{C,D} \cdot \eta_{Tr} \cdot \eta_M \cdot P_{m,compr} + \dot{Q}_{th,NG}}$$

$$x_{C,D} = \frac{\Delta t_C}{\Delta t_D}$$

- $x_{C,D}$: Time-factor = full load charging time / full load discharging time (e.g. CAES Huntorf: $x_{C,D} = 4$; CAES McIntosh: $x_{C,D} = 1{,}6$)
- Time-factor depends on storage period, i.e. time-dependent losses have to be considered (e.g. evaporation of liquid air in terms of a CES system)
- Adiabatic systems: no thermal energy of fuel ($\dot{Q}_{th,NG} = 0$)
- Two energy inputs with different energy qualities: electricity and thermal power of fuel
- Lower energy quality of fuel has to be considered (→ Storage efficiency)

Storage efficiency (1):

$$\eta_{storage,1} = \frac{E_{el,released} - \eta_{NG} \cdot E_{th,in}}{E_{el,in}} = \frac{\eta_{Tr} \cdot \eta_{Gen} \cdot P_{m,T} - \eta_{NG} \cdot \dot{Q}_{th,NG}}{x_{C,D} \cdot \eta_{Tr} \cdot \eta_M \cdot P_{m,compr}}$$

- η_{NG} consideres energy quality of fuel input in **output correction term** ($\eta_{NG} \cdot \dot{Q}_{th,NG}$)
- Output correction term is amount of electricity that could be have been made from the natural gas, had that fuel been used to make electricity in a stand-alone power plant at efficiency η_{NG} instead of to fire a CAES/CES unit
- Strong dependency of $\eta_{storage,1}$ on η_{NG} (see Figure 2)
- Choice of η_{NG} according to plant output of CAES/CES (see Figure 3)

- Adiabatic systems (index ad): no thermal energy of fuel ($\dot{Q}_{th,NG} = 0$)
  → $\eta_{storage,1,ad} = \eta_{RT,ad}$

<u>Storage efficiency (2):</u>

$$\eta_{storage,2} = \frac{E_{el,released}}{E_{el,in} + \eta_{NG} \cdot E_{th,in}} = \frac{\eta_{Tr} \cdot \eta_{Gen} \cdot P_{m,T}}{x_{C,D} \cdot \eta_{Tr} \cdot \eta_M \cdot P_{m,compr} + \eta_{NG} \cdot \dot{Q}_{th,NG}}$$

- η_{NG} consideres energy quality of fuel input in **input correction term** ($\eta_{NG} \cdot \dot{Q}_{th,NG}$)
- Input correction term is amount of electricity that could be have been made from the natural gas, had that fuel been used to make electricity in a stand-alone power plant at efficiency η_{NG} instead of to fire a CAES/CES unit
- Strong dependency of $\eta_{storage,2}$ on η_{NG} (see Figure 2)
- Choice of η_{NG} according to plant output of CAES/CES (see Figure 3)
- Adiabatic systems (index ad): no thermal energy of fuel ($\dot{Q}_{th,NG} = 0$)
  → $\eta_{storage,2,ad} = \eta_{RT,ad}$

<u>Fuel efficiency</u>

$$\eta_F = \frac{E_{el,released}}{E_{th,in}} = \frac{\eta_{Tr} \cdot \eta_{Gen} \cdot P_{m,T}}{\dot{Q}_{th,NG}}$$

- Thermodynamic efficiency of conversion of thermal power from fuel to electricity
- Separately from overall process → no "storage efficiency"
- Corresponds to Heat Rate (HR) of conventional power plants
- Examples:
  - Hitachi H-25 Gas Turbine: P_{el} = 41,9 MW, Heat Rate (LHV) = 9670 kJ/kWh
  - Hitachi H-25 Combined Cycle (1-1-1): P_{el} = 57,7 MW, Heat Rate (LHV) = 6963 kJ/kWh
  - CES (exemplary LAES process): $P_{el,D}$ = 93 MW, $\dot{Q}_{th,NG}$ = 106 MW, Heat Rate (LHV) = 4103 kJ/kWh
- Not suitable for adiabatic systems due to no fuel consumption

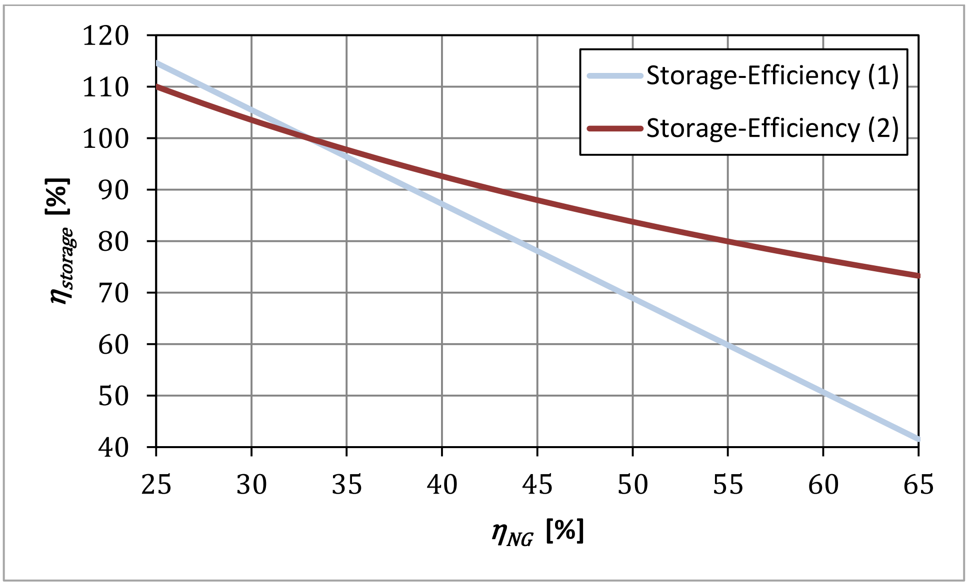

Figure 2 Dependency of Storage efficiency on efficiency of stand-alone power plant η_{NG} (reference: CES(LAES) with $P_{el,C}$ = 58 MW, $P_{el,D}$ = 93 MW, $Q_{th,NG}$ = 106 MW, $x_{C,D}$ = 1).

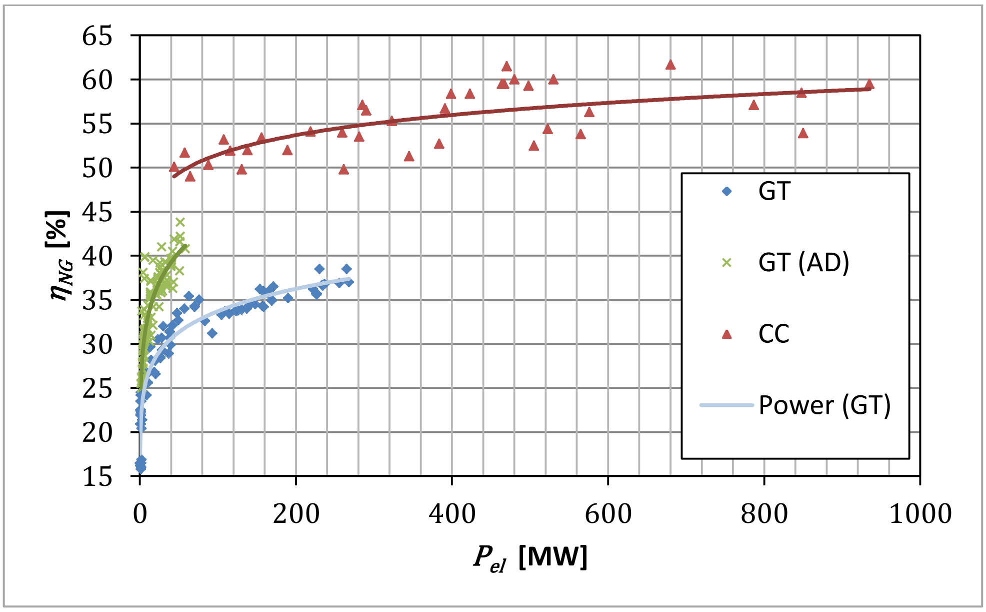

Figure 3 Efficiency of stand-alone power plant fueled by natural gas; GT = gas turbine power plant; AD = aeroderivative gas turbine power plant; CC = combined cycle power plant; Pot. = potential function.

Sources: [SUCCAR2008, POULLIKKAS2004]

Cryogenic energy storage (CES)

For cryogenic energy storage the equations for adiabatic/diabatic compressed air can be used. For adiabatic CES systems and systems with waste heat utilization the fuel contribution should not be included.

Pumped hydro

Efficiency formula: defined is the following formula

$$\eta_{global\ cycle} = \frac{E_{el,released}}{E_{el,in}} = \eta_{h,T} \cdot \eta_{m,T} \cdot \eta_{el,T} \cdot \eta_{h,P} \cdot \eta_{m,P} \cdot \eta_{el,P} \cdot \frac{\left(1 - \frac{\Delta H_T}{H_{g,T}}\right)}{\left(1 + \frac{\Delta H_P}{H_{g,P}}\right)}$$

- $\left(1 + \frac{\Delta H_P}{H_{g,P}}\right)$ and $\left(1 - \frac{\Delta H_T}{H_{g,T}}\right)$ represent the head losses, H_g is the gross head in meters and ΔH is the difference between the maximum and minimum net heads
- $\eta_{h,T}$ and $\eta_{h,P}$ are respectively the hydraulic weighted average efficiency of the turbine and the pump
- $\eta_{m,T}$ and $\eta_{m,P}$ are respectively the mechanical efficiency of the turbine and the pump
- $\eta_{el,T}$ and $\eta_{el,P}$ are respectively the electrical efficiency of the turbine and the pump

7. Sources

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European Association
for Storage of Energy

Avenue Adolphe Lacomblé 59/8
B-1030 Brussels
www.ease-storage.eu

Phone +32 (0)2 743 29 82
Fax +32 (0)2 743 29 90
info@ease-storage.eu