ETM521

Lecture 3 – Generation Technologies

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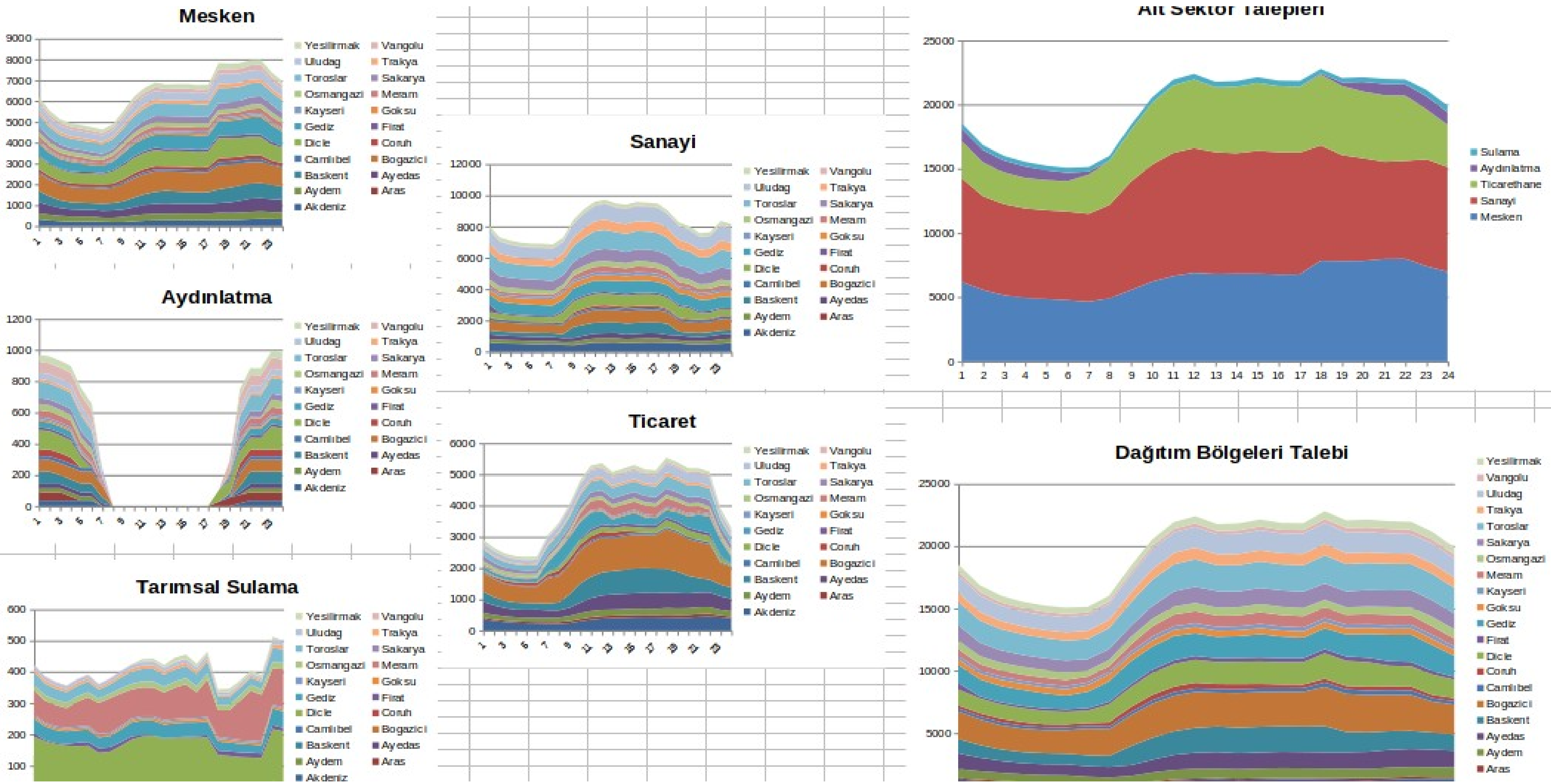
Question

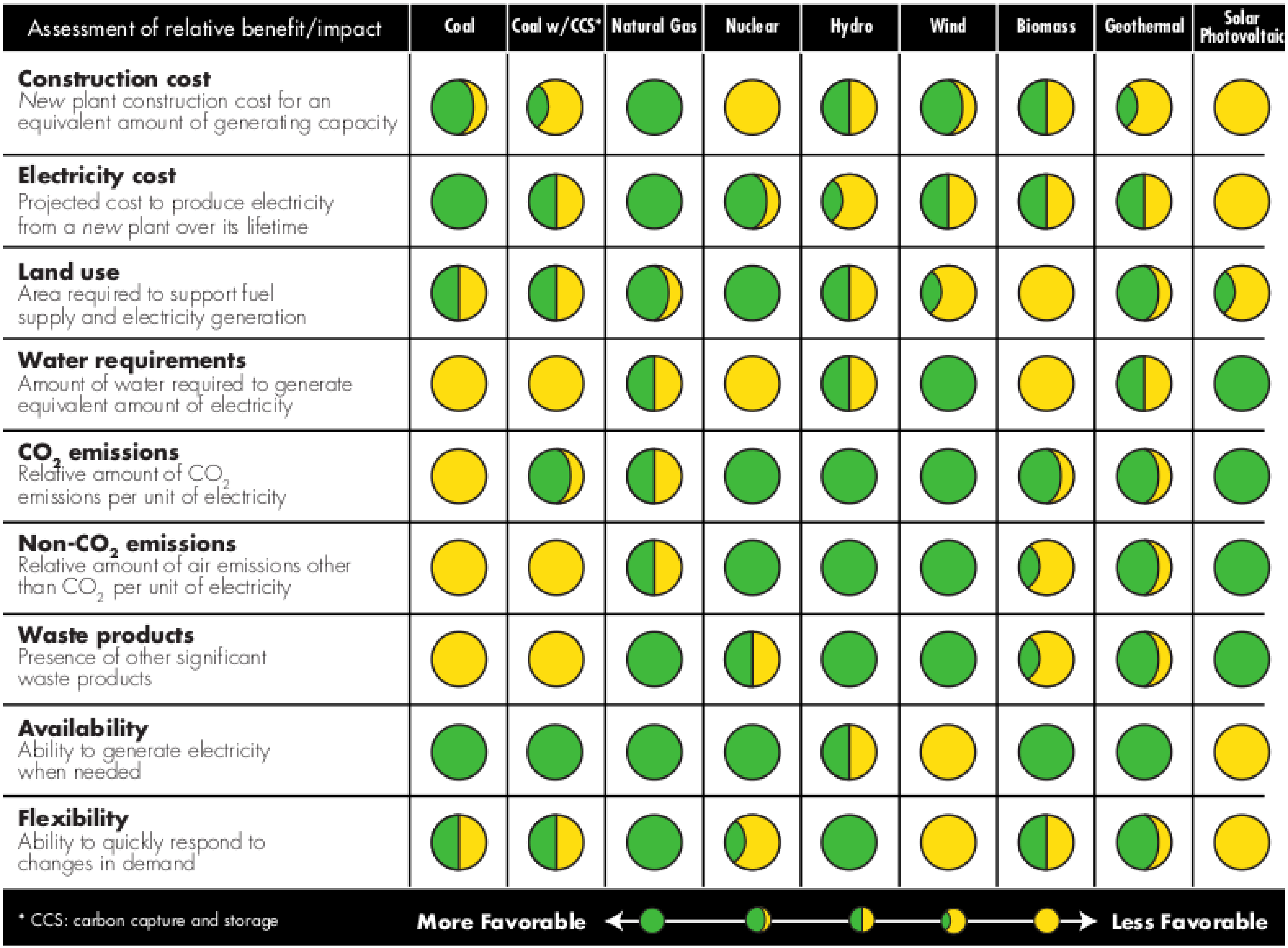
A fund provided you with 100 million $ for electricity generation.

- How will you invest?
- What will be your optimal portfolio?
- What should be your initiating question

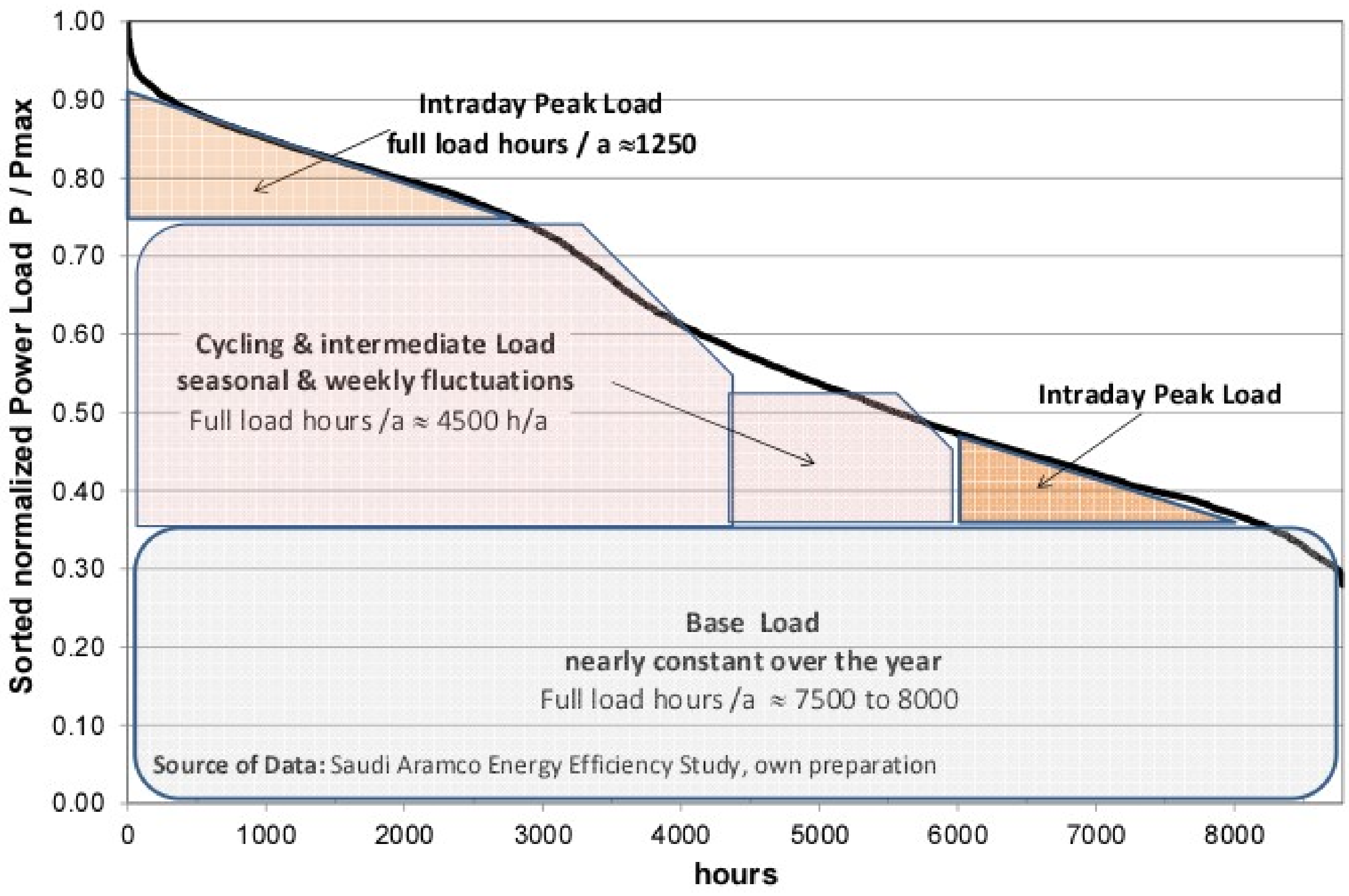
Load profiles



Generation technologies

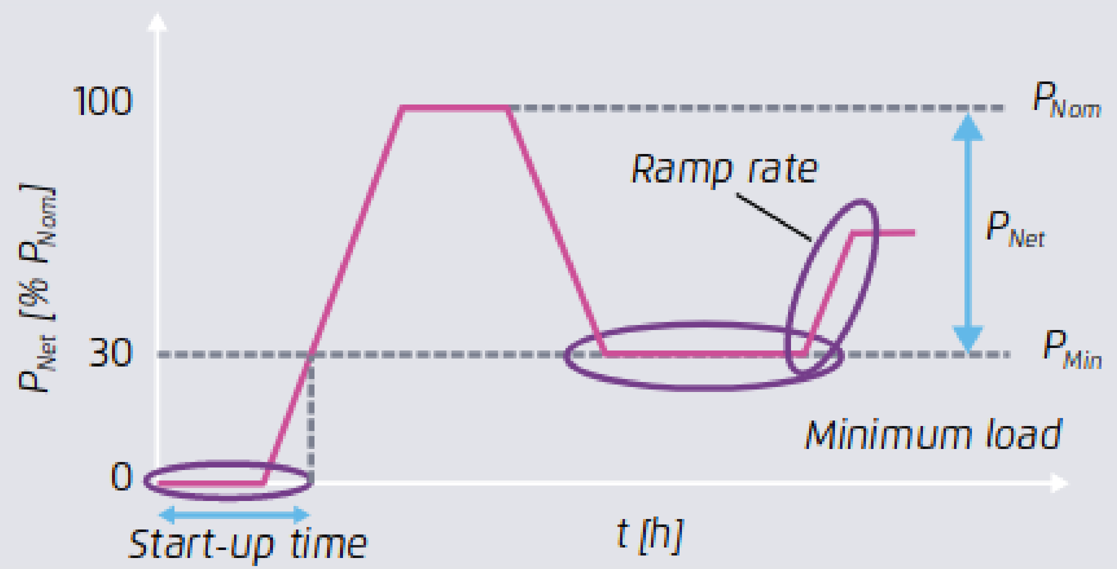


Load duration



Flexibility

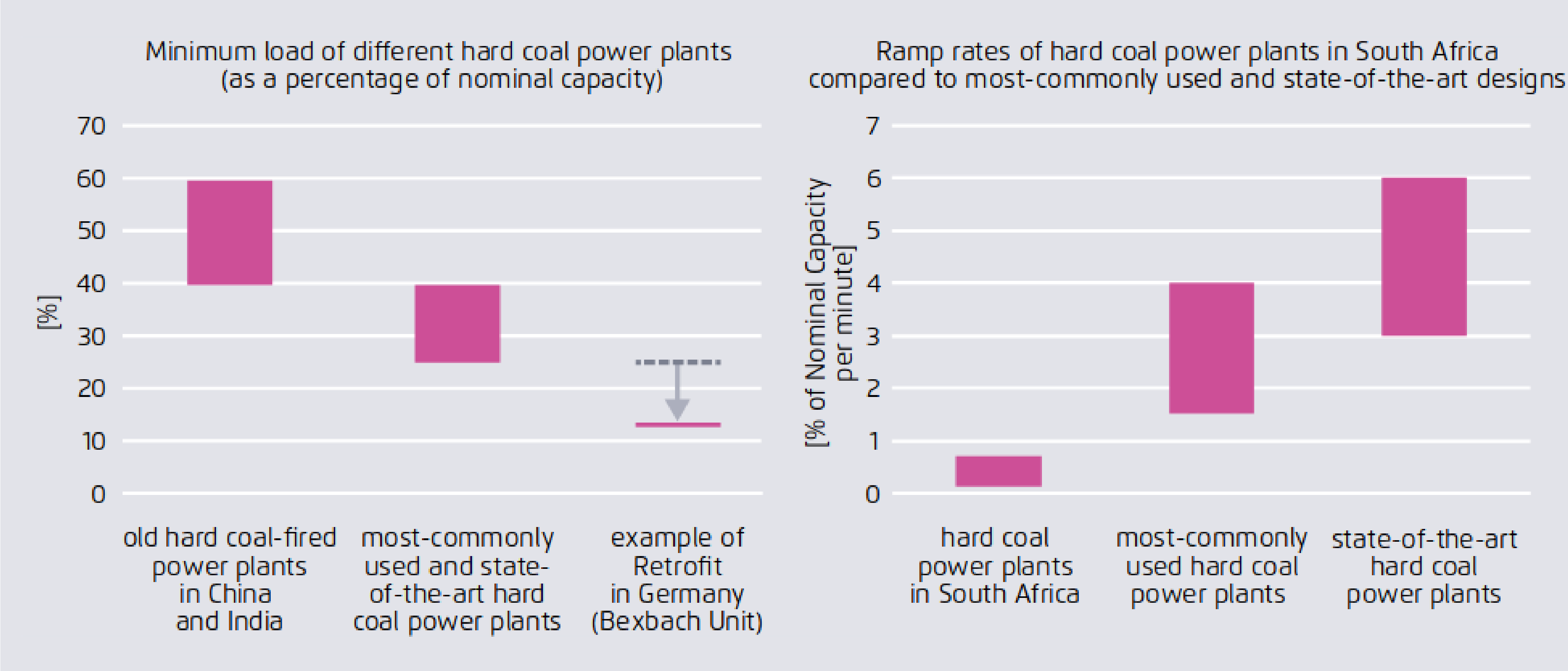
Qualitative representation of key flexibility parameters of a power plant



Fichtner (2017)

Minimum load and ramp rates

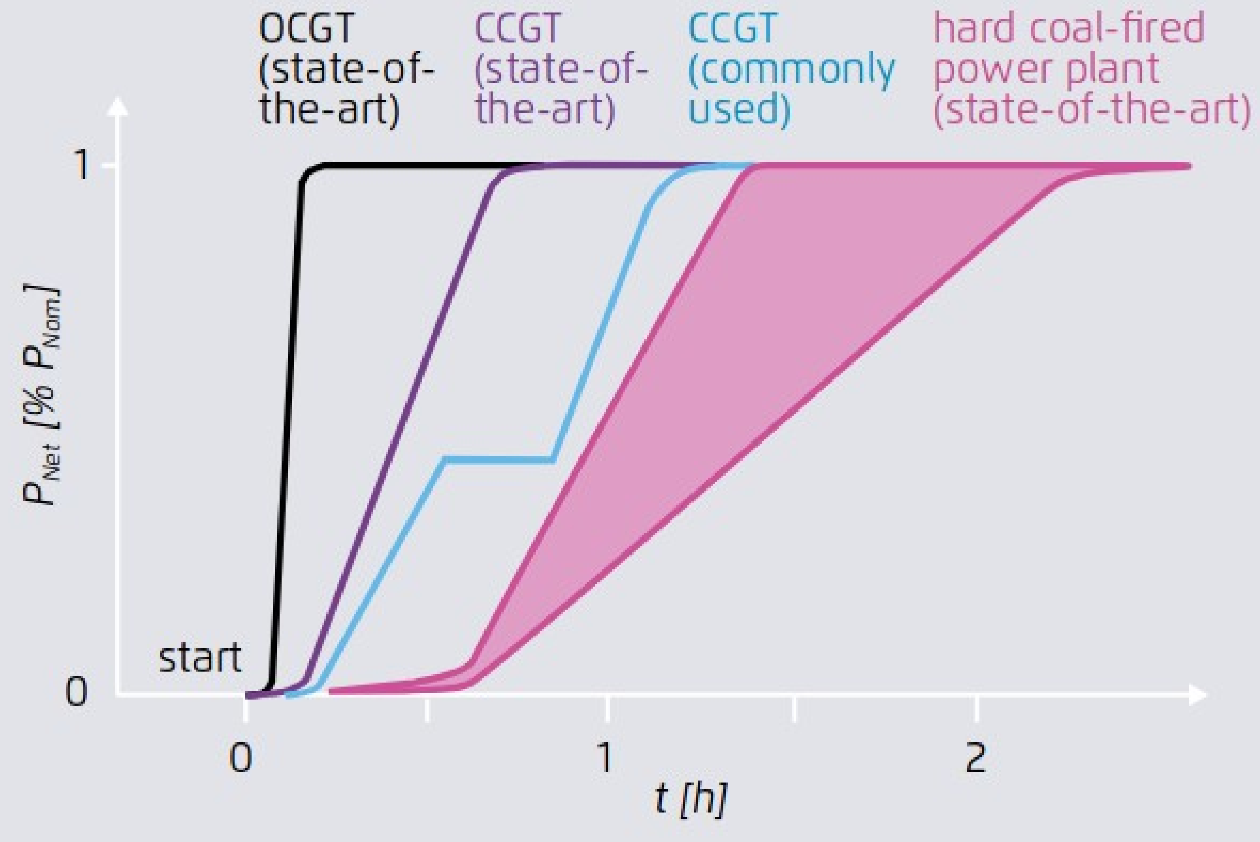
Minimum load and ramp rates of different hard coal power plants　Figure S3



DEA, NREL, Fichtner (left), Prognos, Fichtner (right)

Ramp rates

Ramp rates and start-up times of different power plant technologies



Fichtner (2017) based on (VDE, 2012)

Comparison of most commonly used and state-of-the-art power plants for each generation technology with regard to flexibility

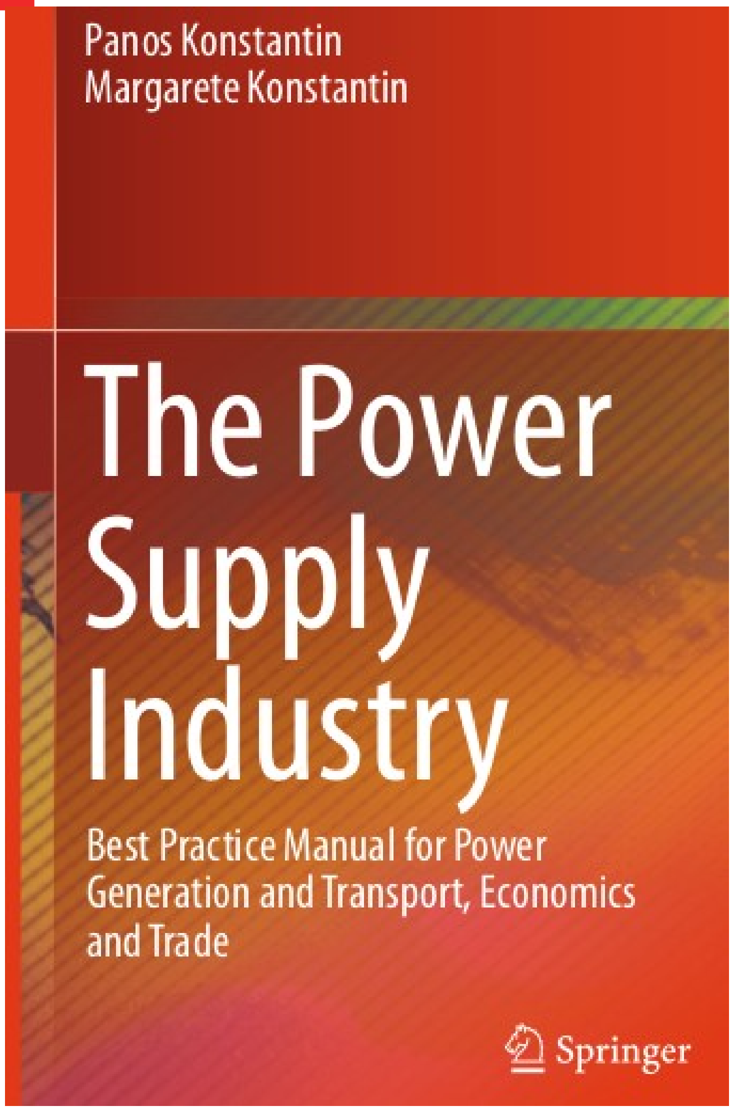
Comparison of most commonly used and state-of-the-art power plants for each generation technology with regard to flexibility

Table 1

Property	OCGT	CCGT	Hard coal-fired power plant	Lignite-fired power plant
Most commonly used power plants				
Minimum load [% P_{Nom}]	40–50 %	40–50 %	25–40 %[a]	50–60 %
Average ramp rate [% P_{Nom} per min]	8–12 %	2–4 %	1.5–4 %	1–2 %
Hot start-up time [min] or [h]	5–11 min[b]	60–90 min	2.5–3 h	4–6 h
Cold start-up time [min] or [h]	5–11 min[c]	3–4 h	5–10 h	8–10 h
State-of-the-art power plants				
Minimum load [% P_{Nom}]	20–50 %	30–40 % (20% with SC[d])	25[e]–40 %[f]	35[g]–50 %
Average ramp rate [% P_{Nom} per min]	10–15 %	4–8 %	3–6 %	2–6[h] %
Hot start-up time [min] or [h]	5–10 min[i]	30–40 min	80 min–2.5 h	1.25[j]–4 h
Cold start-up time [min] or [h]	5–10 min[i]	2–3 h	3–6 h	5[k]–8 h

a Source: (Heinzel, Meiser, Stamatelopoulos, & Buck, 2012)

Resources



- Chapter 1 – Thermodynamics (Examples Ch. 1)
- Chapter 2 – Fundamentals Power Generation (Examples Ch. 2)
- Chapter 3 – Fossil Power Plants (Examples Ch. 3)
- Chapter 4 – Nuclear Power Plants (Examples Ch. 4)
- Chapter 5 – Renewable (Examples Ch. 5.1, Ch. 5.2-5.5, Ch. 5.6-5.8, Ch. 5.9)
- Chapter 6 – Cogeneration (Examples Ch. 6)
- Chapter 7 – Cost Allocation: Cogen (Examples Ch. 7.1, Ch.7.2-7.10)
- Chapter 8 – Transmission and Distribution (Examples Ch. 8)

- Case Study 1 – Rankine Cycle (in T-s-Diagram) calculated with FluidEXL (CS1)
- Case Study 2 – Simulation simple Rankine Cycle (CS2)
- Case Study 3 – Demo – Rankine Cycle Development (CS3)
- Case Study 4 – Integrated Model – techno-economics Fosil-PPs (CS4)
- Case Study 5 – Integrated Model – techno-economics Nuclear-PPs (CS5)
- Case Study 6 – Cashflow, IRR-Analysis Wind farm (CS6)
- Case Study 7 – Integrated Model techno-economics Parabolic trough (CS7)
- Case Study 8 – Integrated Model techno-economics Solar Tower (CS8)
- Case Study 9 – Cost-Allocation: electric equivalent extraction – condensing CHP (CS9)
- Case Study 10 – Cost-Allocation: exergy balance – backpressure CHP (CS10)
- Case Study 11 – Modelling Simulation extraction – condensing Rankine-Cycle no Reheat (CS11)
- Case Study 12 – Modelling Simulation extraction – condensing Rankine-Cycle Reheat (CS12)
- Case Study 13 – Modelling Simulation extraction – condensing CCGT-Cycle (CS13)

http://www.pk-energie-praxiswissen.com/?page_id=479&lang=en

Resources

https://energy.mit.edu/wp-content/uploads/2016/12/Utility-of-the-Future-Full-Report.pdf

https://www.agora-energiewende.de/fileadmin2/Projekte/2017/Flexibility_in_thermal_plants/115_flexibility-report-WEB.pdf

Value of generation to the sys.

	LOCATIONAL	NON-LOCATIONAL
POWER SYSTEM VALUES	• Energy • Network capacity margin • Power quality • Reliability and resiliency • Black-start	• Firm generation capacity[1] • Operating reserves[1] • Price hedging
OTHER VALUES	• Land value/impacts • Employment • Premium values[2]	• CO_2 emissions mitigation • Energy security

Carnot verimliliği

- Carnot verimliliği
- 1- To/T1

Example 1-8: Electrical efficiency of gas turbine vs. Carnot cycle

The gas temperature at the entry of a modern gas turbine is 1200°C, the air inlet temperature to the compressor is 15°C. The maximum plant efficiency in a state-of-the-art simple cycle gas turbine cycle (SCGT) is 44%, in a combined gas-steam turbine cycle (CCGT) it is 60%. What is the maximum efficiency of the Carnot cycle between the two temperatures? What is the theoretical improvement potential?

Carnot efficiency: $$\eta_c = 1 - \frac{273+15}{273+1200} = 0.8 \text{ or } 80\%$$

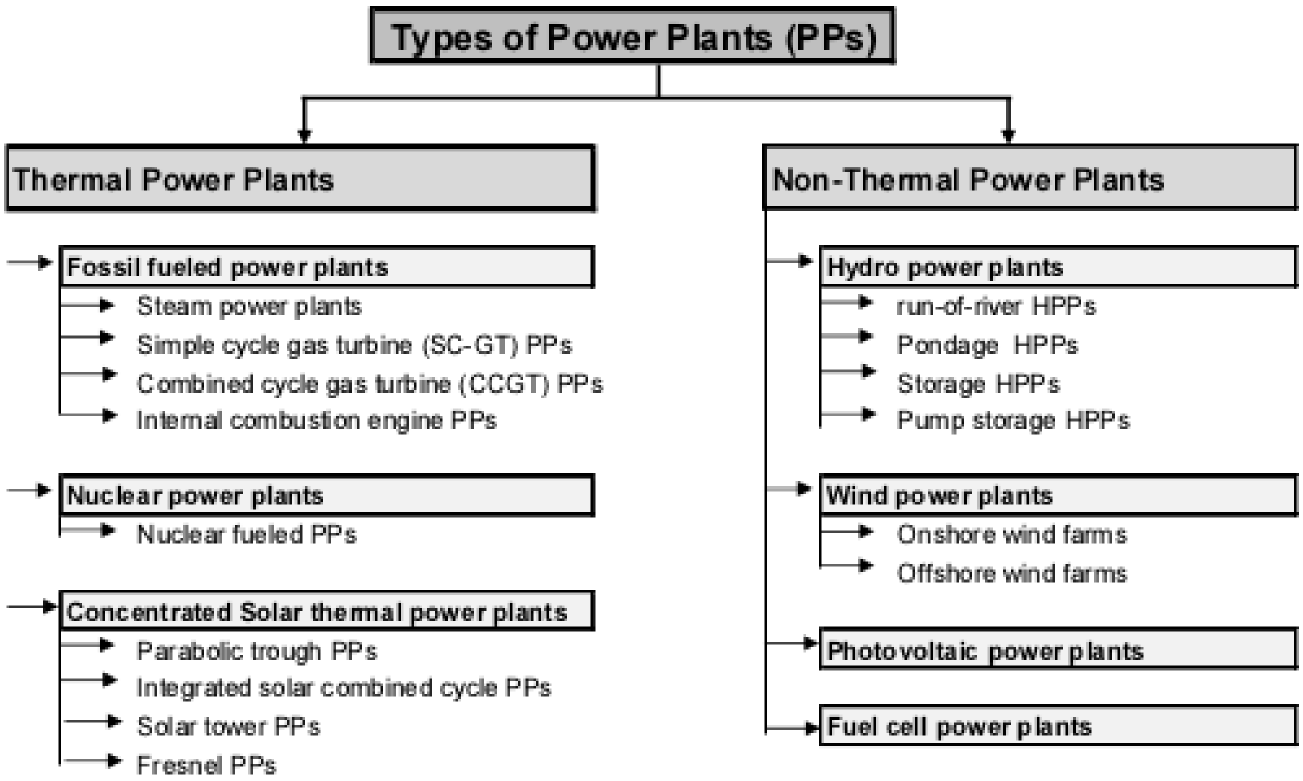
The theoretical improvement potential is 20 percentage points.

Heating Values

- American English
  - LCV : Lower heating value
  - HCV: Higher heating value
- British English
  - NCV – net calorific value
  - GCV – gross calorific value
- Lower heating value does not include condensation heat of water vapor

Fuel	LHV/HHV
Natural gas	0.903
Heating oil	0.940
Hard coal	0.958

Types of Power Plants



Reference site conditions

- Performance is defined with energy efficiency or the heat rate
- Rated power is the performance (kW, eff) based on refence site conditions (RSC)

$$\text{Electrical Efficiency: } \eta_{gross} = \frac{P_{gross}\,[\mathrm{kW_e}]}{\dot{Q}_{LHV}\,[\mathrm{kJ/s}]} \times 100 \quad [\%]$$

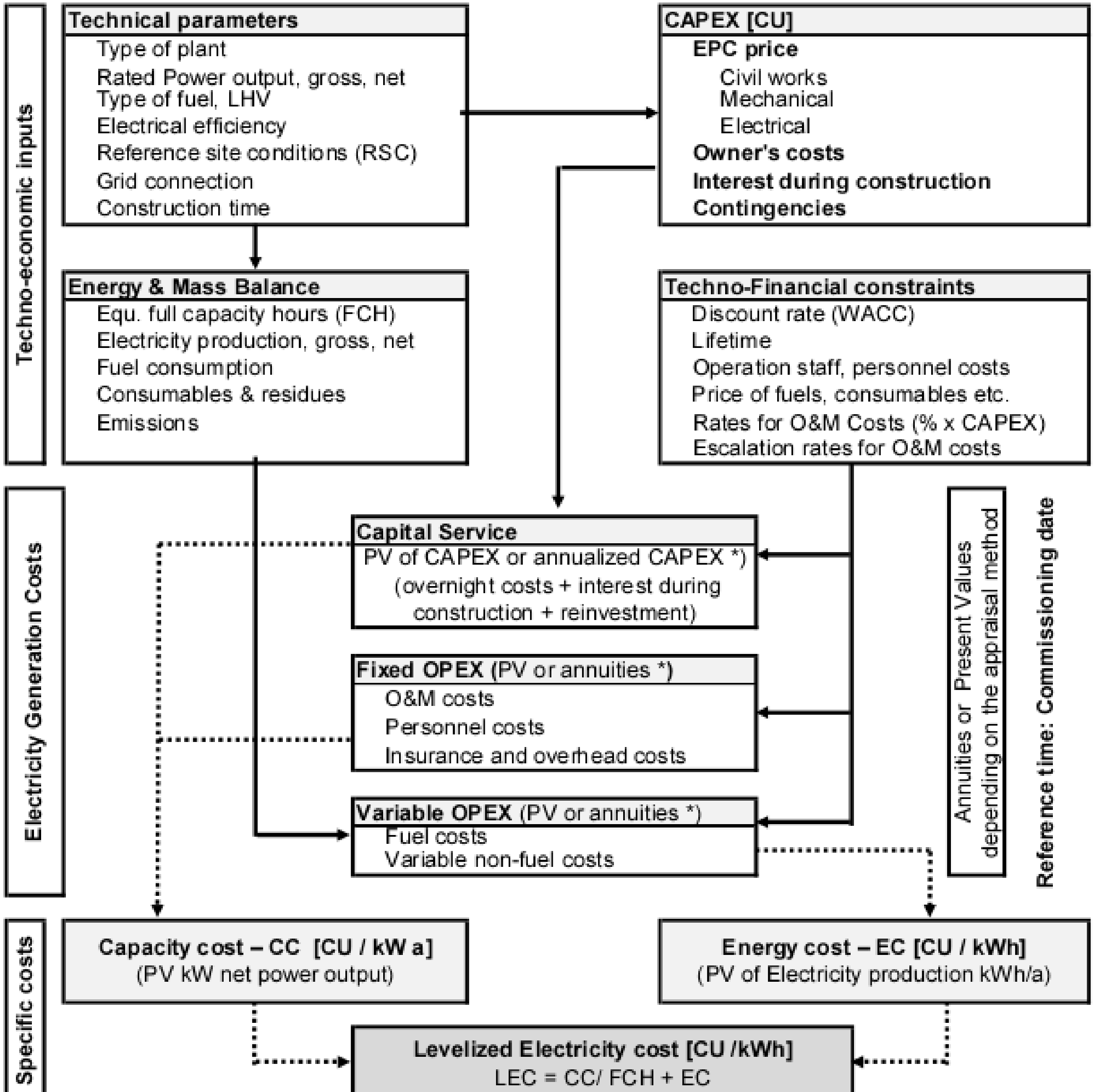
$$\text{Heat rate: } \quad q = 3600 \times \frac{\dot{Q}_{LHV}}{P_{gross}} \quad \left[\frac{\mathrm{kJ}}{\mathrm{kWh_e}}\right]$$

Site	Condenser Cooling	Ambient Temperature °C	Cooling water inlet °C
Europe, North Sea	Seawater once through	15	12
Central Europe	Cooling tower	15	25
Gulf	Seawater once through	46	36

Operating hour

- Operating hours/Running Hours -> time the plant is in operation
- Equivalent Full Capacity Hours -> the equivalent time period during which the power plant would have produced the same amount of electrical power at full power output
- Capacity Factor (CF) : produced/ could have been produced at continuous operation at full power
- Availability : is the state where a unit can provide energy within a reference period (IEEE-762-2006)
  - Planned outages: Maintenance
  - Forced outages: Failures during operation

Cost structure



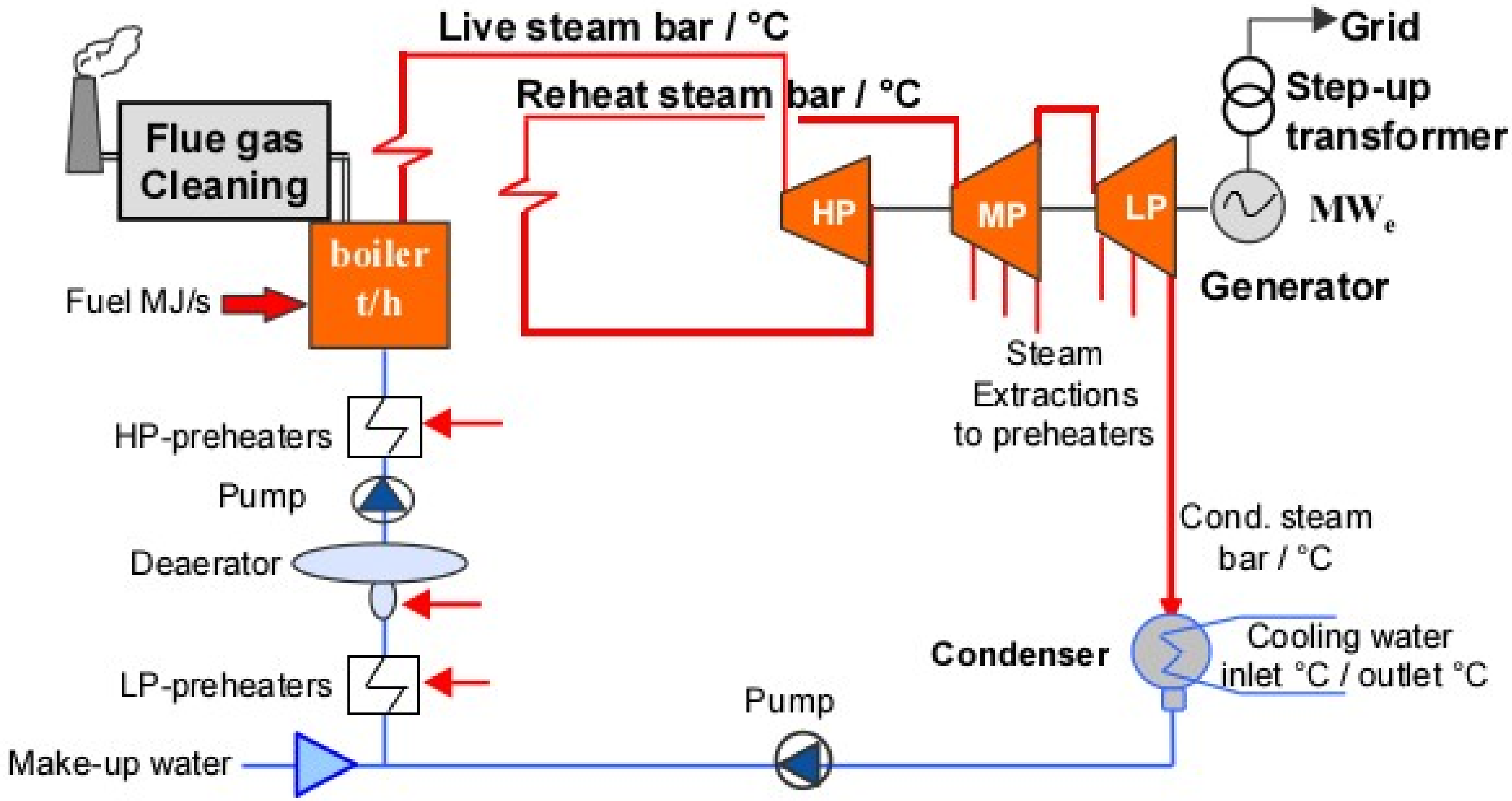
CAPEX estimate

Item		Unit	Steam PP	CCGT PP
Power and energy balance				
Power output, net		MW	600	400
Equivalent operating hours		h / a	5,500	5500
Power generation, net		MWh /a	3,300,000	2,200,000
Efficiency, net		-	42%	55%
Fuel consumption		MWh_t /a	7,857,143	4,000,000
CAPEX, incl. IDC+reinvest		**mln. US$**	**1,343**	**433**
Discount rate, in real terms		% /a	6.5%	6.5%
Lifetime		a	35	25
Fixed OPEX		% Capex	2.50%	1%
Fuel price LHV, w.o. escalation [1)]		US$ / MWh_t	12.29	27.5
Annual OPEX, at start of operation				
OPEX, fixed		mln. US$ /a	33.56	4.33
OPEX variable [2)]	10%	mln. US$ / a	106.18	121.00
Annual costs, incl. escalation for OPEX				
Annualized CAPEX		mln. US$ / a	97.76	35.37
Fixed OPEX [3)]	0.5%/a esc	mln. US$ / a	35.68	4.55
Variable OPEX [3)]	1.5%/a esc	mln. US$ / a	128.26	140.88
Total annual costs		**mln. US$ / a**	**261.71**	**180.80**
Levelized electricity cost		**US$ / MWh**	**79.30**	**82.18**

1) price coal 100 US$/tce natural gas LHV 25 US$/MWh

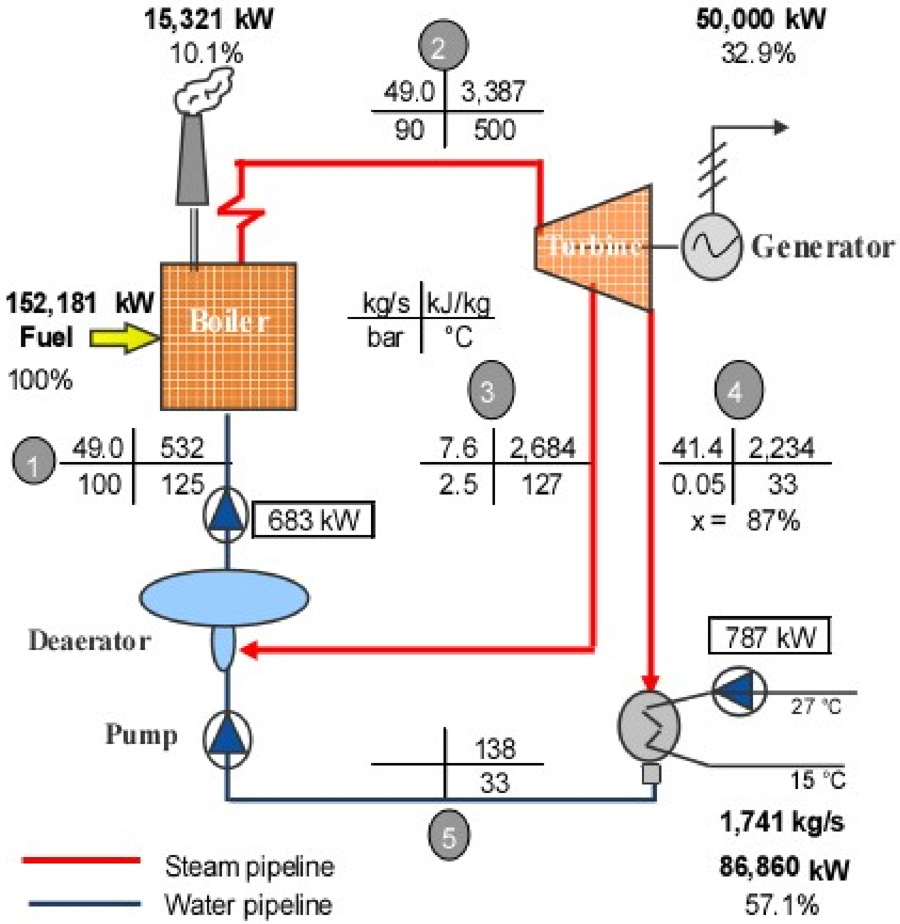
2) fuel + 10% non-fuel costs 3) escalation in real terms

Steam Power Plants



Source: Technologies & Economics, Author's own illustration

Sub-Super- Ultra Critical plants



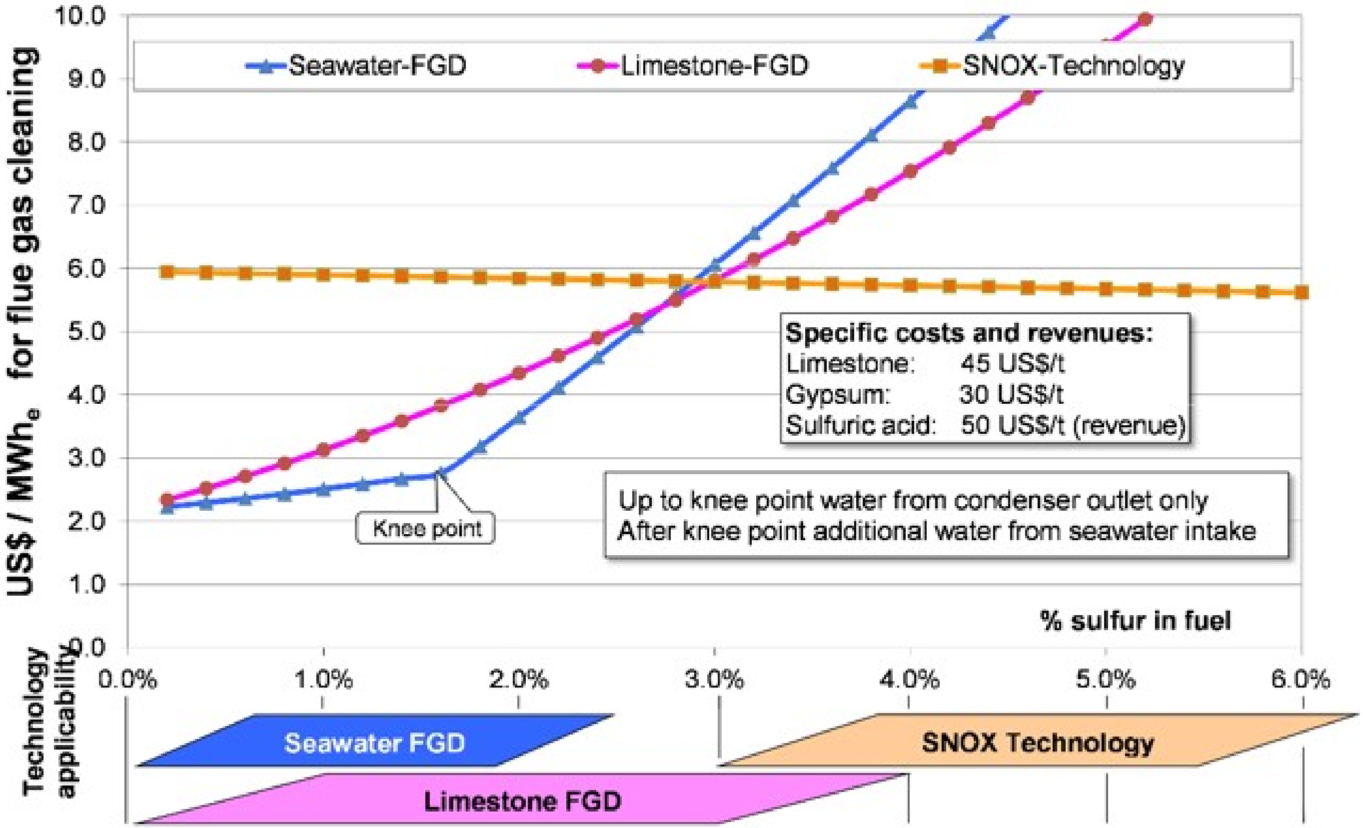
Item	Unit	SubC	SC	USC
Typical rated power capacity	MW	600	800	800
Steam generation	t / h	1,850	2,455	2,040
Live steam parameters	bar / °C	160 / 535	240/ 540	285 / 600
Reheat steam parameters	bar / °C	42 / 535	48 / 540	59 / 620
Cooling water temperature *)	°C	31	31	31
Electrical efficiency, gross	-	42.0%	45.5%	48.5%
Heat rate	kJ / kWh	8,571	7,912	7,423

*) cooling tower, Central Europe

How cooling affects efficiency

Item		Unit	Location	
			North Sea	Gulf
Technical parameters				
Rated capacity, gross		MW	600	
Steam parameters *)		bar /bar /°C	160 / 42 / 535	
Cooling water temperature		°C	15	35
Electrical efficiency, gross **)		-	44.23%	41.75%
Heat rate		MJ / kWh	8.14	8.62
Energy balance				
Equivalent operating hours		h / a	7,500	
Annual electricity generation		GWh_e /a	4,500	
Annual fuel consumption		GWh_t /a	10,175	10,778
Fuel costs				
Fuel price		US$ / t_{ce}	120	
Fuel heat price	8.14 MWh/tce	US$ / MWh_t	14.74	
Annual fuel costs		**mln US$ / a**	**150**	**159**

How sulphur content affects?

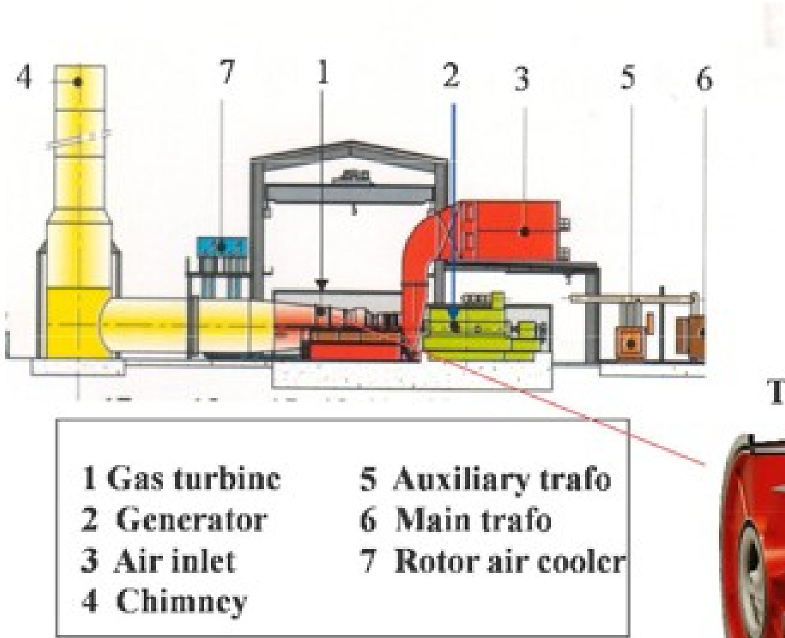


Item	VR	HFO-380	AH	AL
Sulfur in fuel	**5.70%**	**3.70%**	**2.96%**	**1.42%**
Limestone consumption [t/h]	23.48	15.08	11.97	5.50
Gypsum production [t/h]	40.39	25.94	20.59	9.46

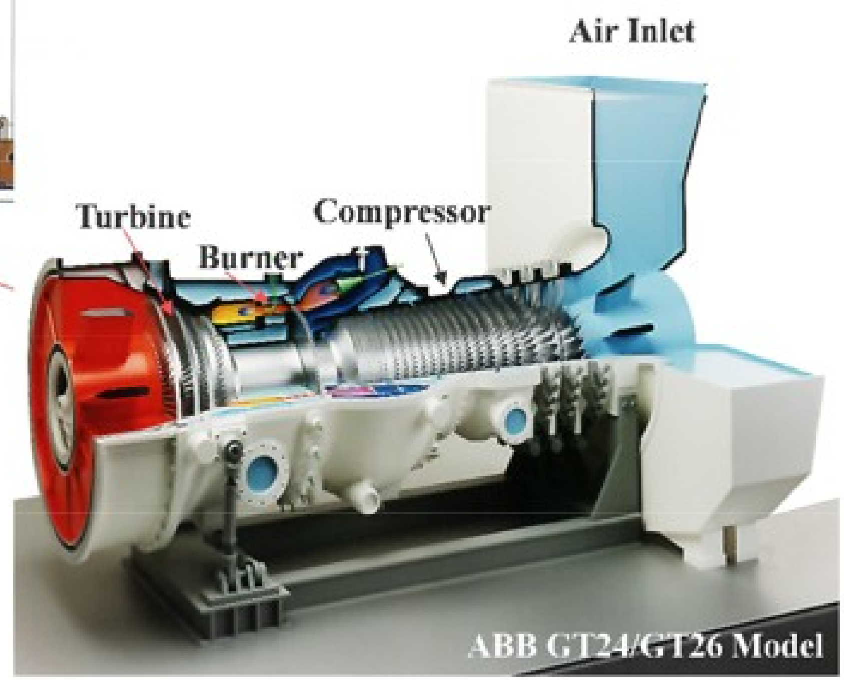
Note: Reference power plant: electrical output 600 MWe, fuel input 1,420 MWt

VR: vacuum residue; HFO: heavy fuel oil; AH: Arabian heavy; AL: Arabian light

Simple cycle gas turbine



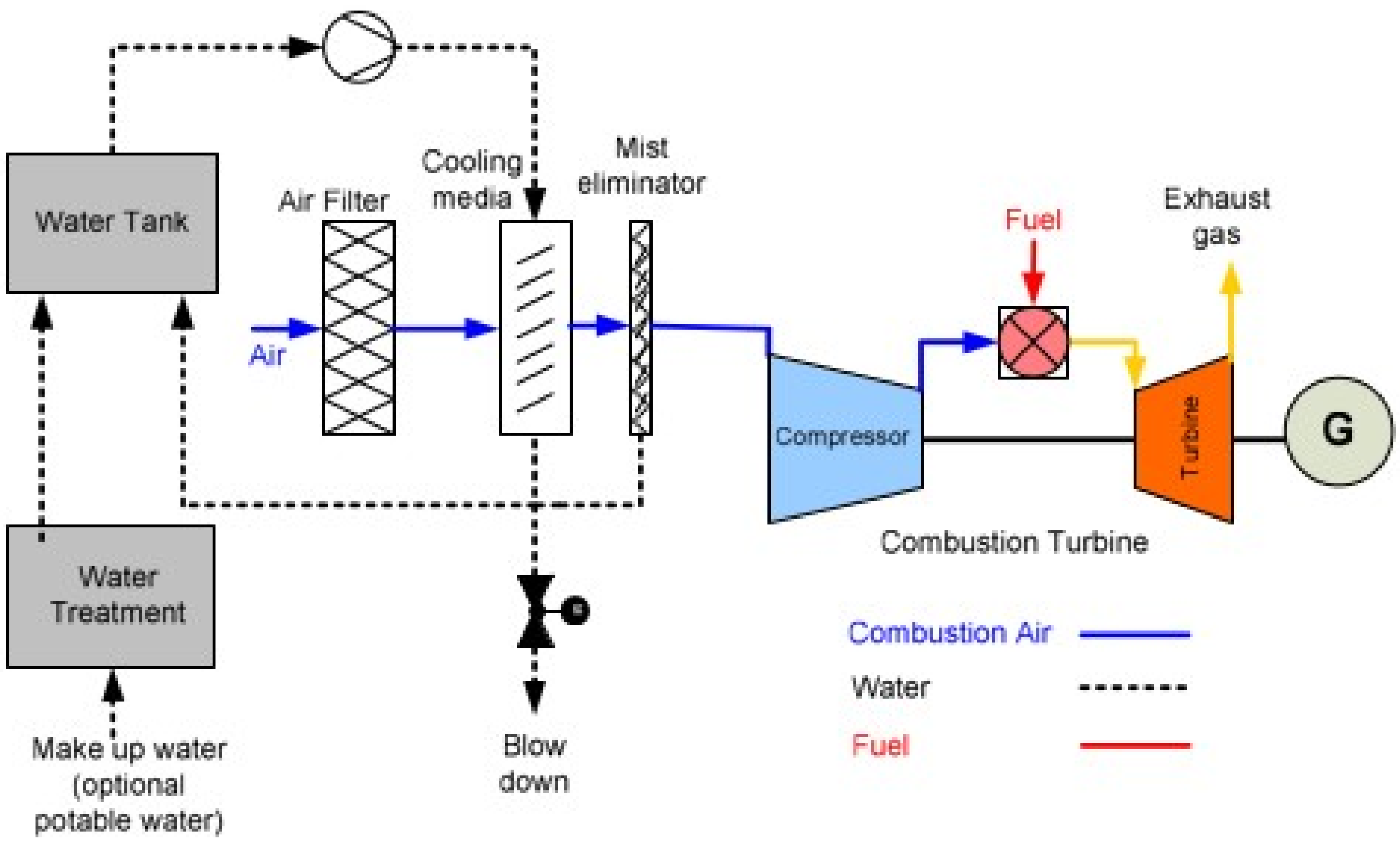
Source: ABB Brochure



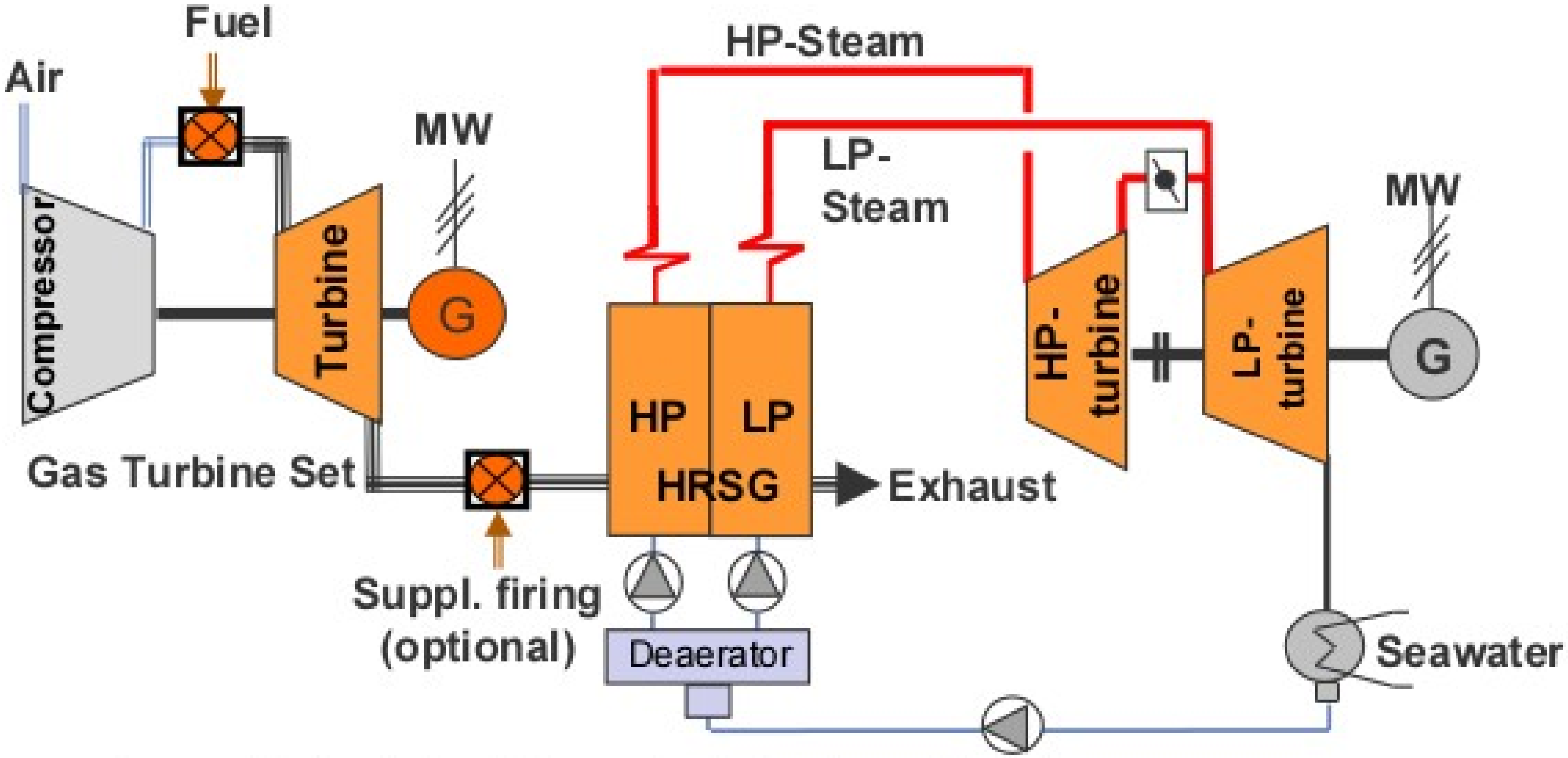
Site conditions on efficiency

Item	Unit	Values	
Technical parameters			
Gas turbine type		STG6-5000F	
Fuel	-	natural gas	
Rated power output, ISO	MW	208	
Electrical efficiency, ISO	-	38.10%	
Location (Saudi Arabia)		**Jazan Red Sea**	**Riyadh Central**
Elevation	m	7	608
Design temperature	°C	38	44
Correction factors:			
Elevation factor for power	-	0.999	0.933
Temperature factor for power	-	0.976	0.972
Temperature factor for efficiency	-	0.949	0.936
Actual power output	**MW**	**203**	**189**
Actual electrical efficiency	**-**	**36.2%**	**35.7%**

Heating inlet air temperature



Combined Cycle

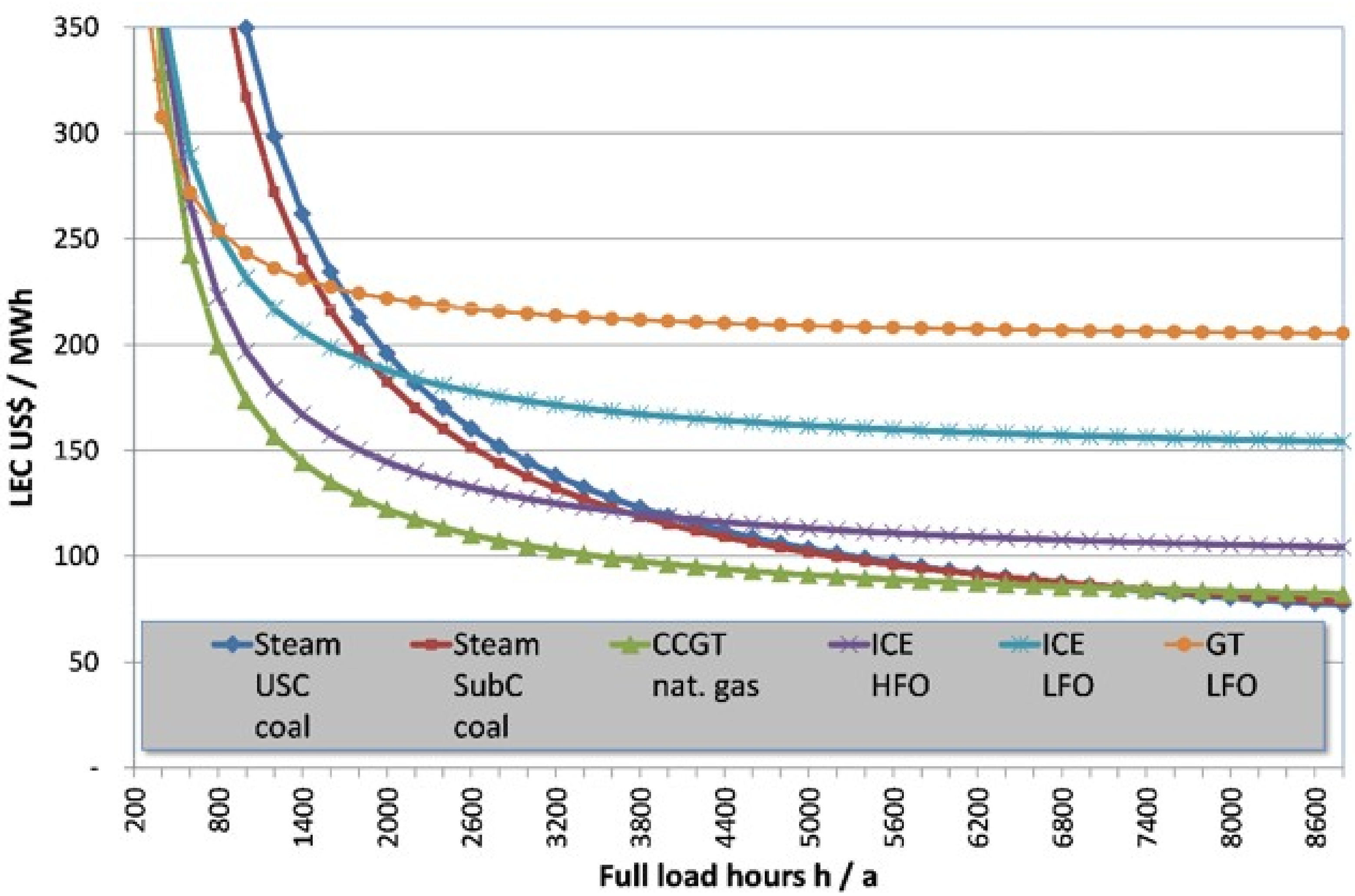


Source: Technologies & Economics, Author's own illustration

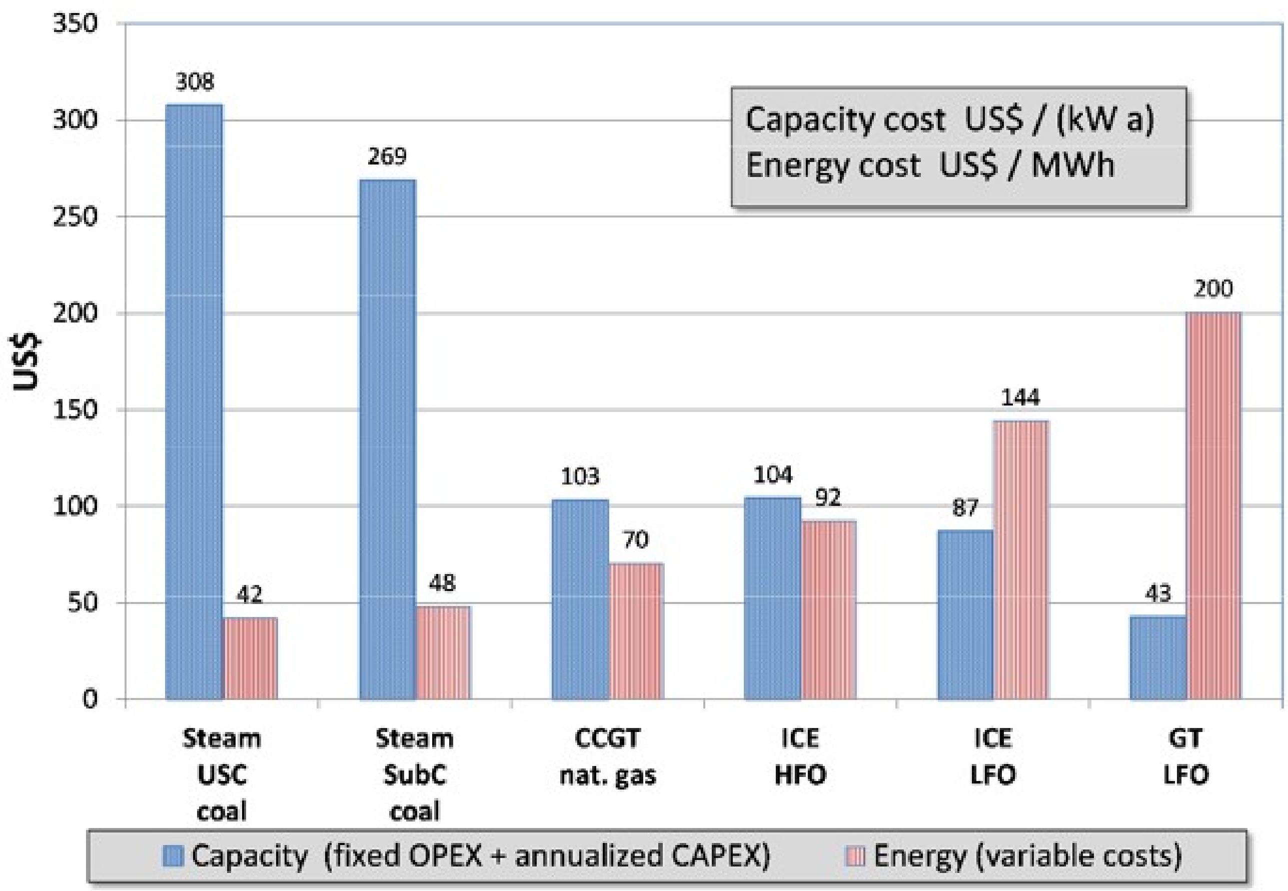
Techno-economics of Fossil Fuel

Item	Unit	Steam USC coal	Steam SubC coal	CCGT nat. gas	IC Engine HFO	IC Engine LFO	GT LFO
Energy balance							
Number of units	-	1	1	1	24	20	2
Power output net	MW	744	555	404	402	335	329
Net electricity production	GWh_e /a	5,566	4,152	1,959	2,009	502	478
Fuel consumption	GWh_t / a	11,843	10,127	3,320	4,481	1,120	1,462
Financial constraints							
Life time	a	35	35	25	25	25	20
Construction time	a	5.0	5.0	2.5	2.0	2.0	1.5
Discount rate (WACC), real terms	% / a	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Fuel price	US$ / MWh_{LHV}	19.3	19.3	39.5	38.0	61.3	61.3
CAPEX, 2014 US$, ±25%	**mln US$**	**2,440.5**	**1,564.2**	**404.3**	**415.0**	**282.3**	**120.6**
Annual power generation costs	**mln US$ / a**	**462.6**	**348.5**	**179.7**	**227.5**	**101.7**	**109.9**
Annualized CAPEX	mln US$ / a	177.7	113.9	33.1	33.9	23.1	10.9
OPEX fixed	mln US$ / a	51.2	35.4	8.6	8.0	6.1	3.2
OPEX variable, incl. fuel costs	mln US$ / a	233.6	199.2	138.0	185.6	72.5	95.8
Power generation cost, levelized							
Capacity (fixed OPEX + Annualized capex)	US$ / (kWa)	307.7	269.0	103.2	104.3	87.1	42.8
Energy (variable cost)	US$ / MWh	42.0	48.0	70.5	92.3	144.3	200.4
Composite cost, excl. CO_2-cost *)	**US$ / MWh_e**	**83.10**	**83.93**	**91.75**	**113.21**	**202.35**	**229.85**
Composite cost, incl. CO_2-cost *))**	**US$ / MWh_e**	**86.74**	**88.10**	**93.46**	**116.34**	**205.32**	**233.92**
*) referred to full load hours	h /a	7,481	7,481	4,850	5,000	1,500	1,455

Electricity Generation Costs

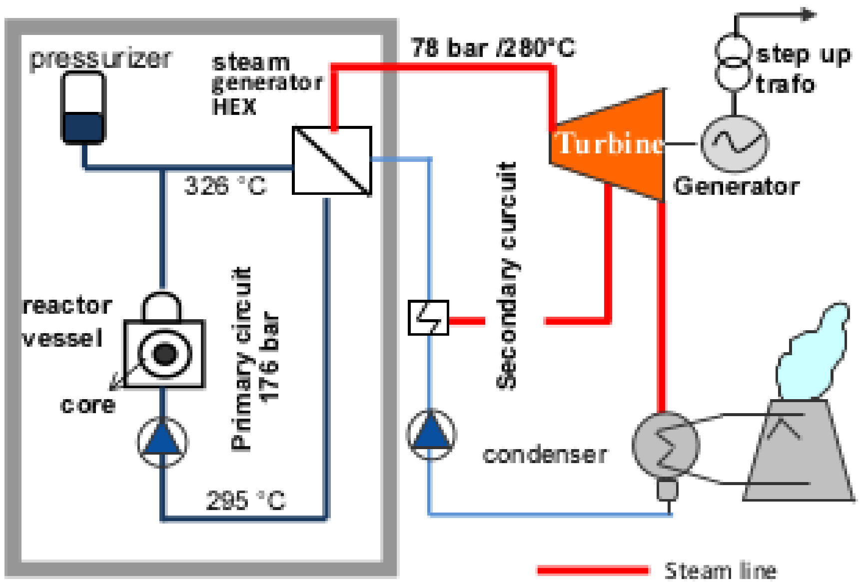


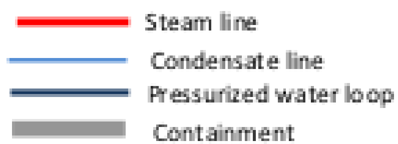
Structure of electricity gen costs



Nuclear Power

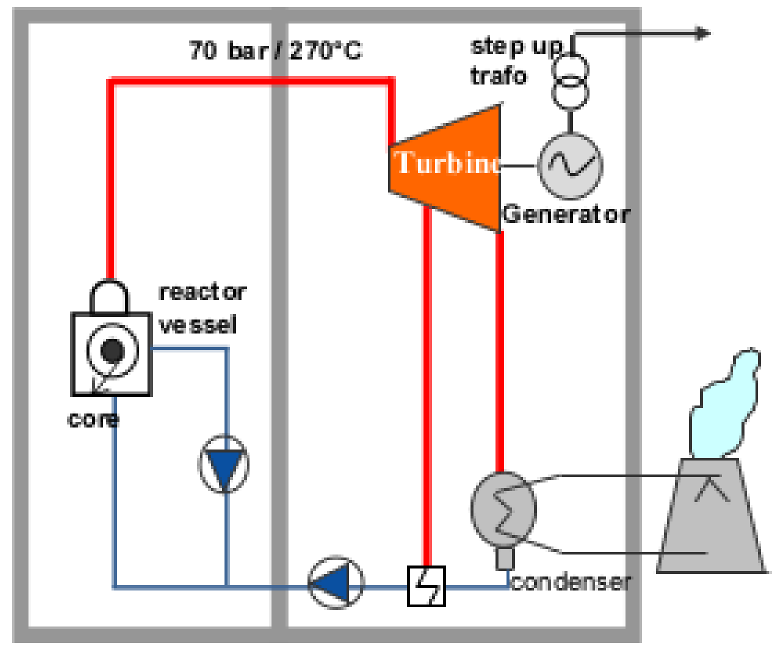
Pressurized Water Reactor – PWR





Source: Authors own compilation
(Technical paremeters as EPR)

Boiling Water Reactor – BWR



Item		Unit	Standard	EPR
Fuel burnup		MW_t d / kg	45	65
Time		h /d	24	24
Equivalent heating value		MWh /kg	1,080	1,560
	3600	MJ /kg	3,888,000	5,616,000

Nuclear Economics

Component	Explanation	Units needed for 1 kg UO_2*)	US$/Unit **)	Total
Uranium oxide U_3O_8	This is the form Uranium is offered in the market place. It includes 0.7% of the fissile isotope U-235.	8.90 kg U3O8	72.64	646
Conversion in UF_6	The Uranium oxide is converted in gaseous form in Uranium hexafluoride (UF_6).	7.50 kg U	7.92	59
Enrichment	Uranium hexafluoride (UF_6) is in enriched in centrifuges to enriched UF_6 with a concertation of 3 to 4 percent U-235.	7.30 kg SWU	91.83	670
Fuel fabrication	The enriched UF_6 is converted in Uranium dioxide (UO_2), the actual nuclear fuel, in form of powder. It is compressed in pellets and filled in thin pipes bundle up in fuel assemblies.	-	-	275
Nuclear fuel	Assemblies of nuclear fuel	**1 kg UO_2**	**-**	**1,651**

*) **Source:** World Nuclear Association, information library, July 2015

	Symbols	Unit	Conventional Steam PP	Advanced Nuclear PP	
Type	-	-	USC	EPR -Areva	
Fuel	-	-	hard coal	UO_2	
Number of units	-	-	2	1	1
Rated power output, per unit, gross	P_e	MW_e	875	1,750	1,750
Rated thermal power	P_t	MW_t	1,804	4,590	4,590
Electrical efficiency, gross		-	48.5%	38.1%	38.1%
Heat value LHV/ Fuel burnup	-	-	8.14 GWh/t	1,560 GWh/t	65 GWd/t
Equivalent full load hours	t	h /a	7,500	7,500	7,500
		d / a	n.a.	n.a.	312.5
Electricity generation	$W_e = P_e \times t$	GWh_e /a	13,125	13,125	13,125
Fuel consumption ➡	$Q = W_e / \eta$	**GWh_t /a**	**27,062**	**34,425**	**34,425**
	m	**t /a**	**3,325**	**22.1**	**22.1**
Formula	$m =$	t /a	Q / LHV	Q / LHV	$P_t \cdot t / burnup$

Technoeconomics

Item		Unit	Value
Power and Energy balance		-	
Rated power each, total, gross		MW_e	2,400
Thermal reactor power, total		MW_t	6,800
Electricity generation, net	7,500 h/a	GWh_e / a	16,740
Fuel consumption, in thermal units		GWh_t / a	47,430
metric tons nuclear fuel		t / a	35.4
Technical-financial constraints			
Service life for calculation		a	50
Discount rate, on real terms (WACC)		% / a	7.1%
Cost of nuclear fuel *)		US$ / kg UO_2	1,651
Reserve funds for decommissioning, waste disposal		US$ / MWh_e	3.65
Capital expenditures (CAPEX), US$ 2013 **)		**Mln US$**	**13,720**
Annual costs, US$ 2013		**Mln US$ /a**	**1,483**
Annualized CAPEX		Mln US$ /a	1,002
Fixed Operating expenses (fixed OPEX)		Mln US$ /a	362
Variable operating expenses (variable OPEX)		Mln US$ /a	120
Capacity cost ref. to net power		**US$ / (kW a)**	**611**
Energy cost, ref. to net electricity production		**US$ / MWh_e**	**7.14**
Composite cost		**US$/ MWh_e**	**88.60**

*) Average 2013, book, Engineering Economics

Hydroelectric

$$P = \eta \times \rho \times g \times \dot{Q} \times h \quad [\text{W}]$$

$$P = 8.34 \times \dot{Q} \times h \quad [\text{kW}]$$

Where:

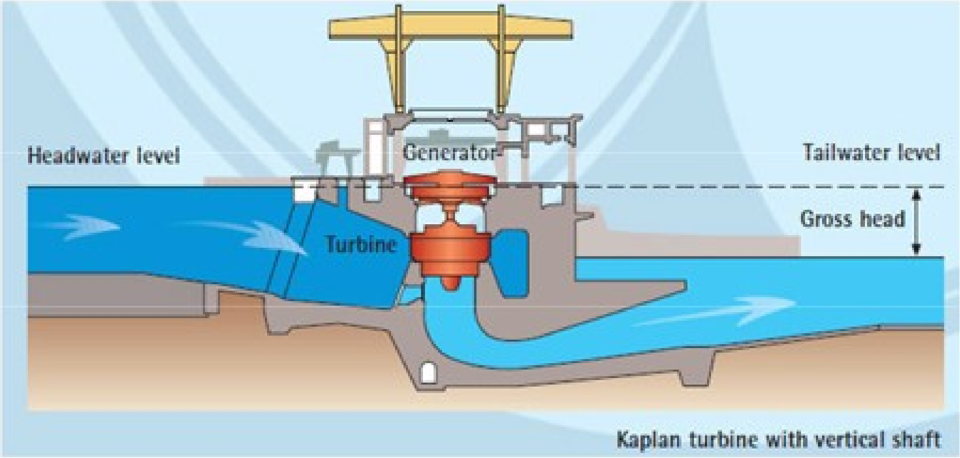
η: System efficiency (0,80 – 0,90)

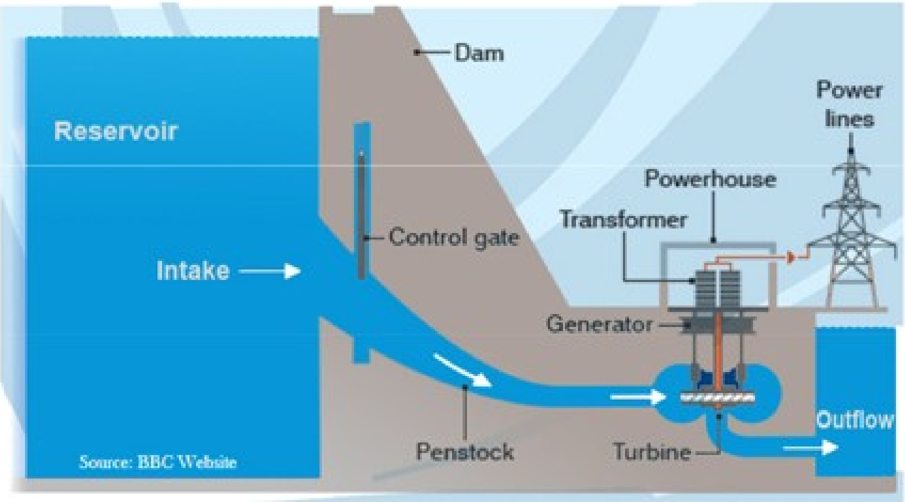
ρ: Density of water (1000 kg/m^3)

g: Gravity acceleration (9,81 m/s)

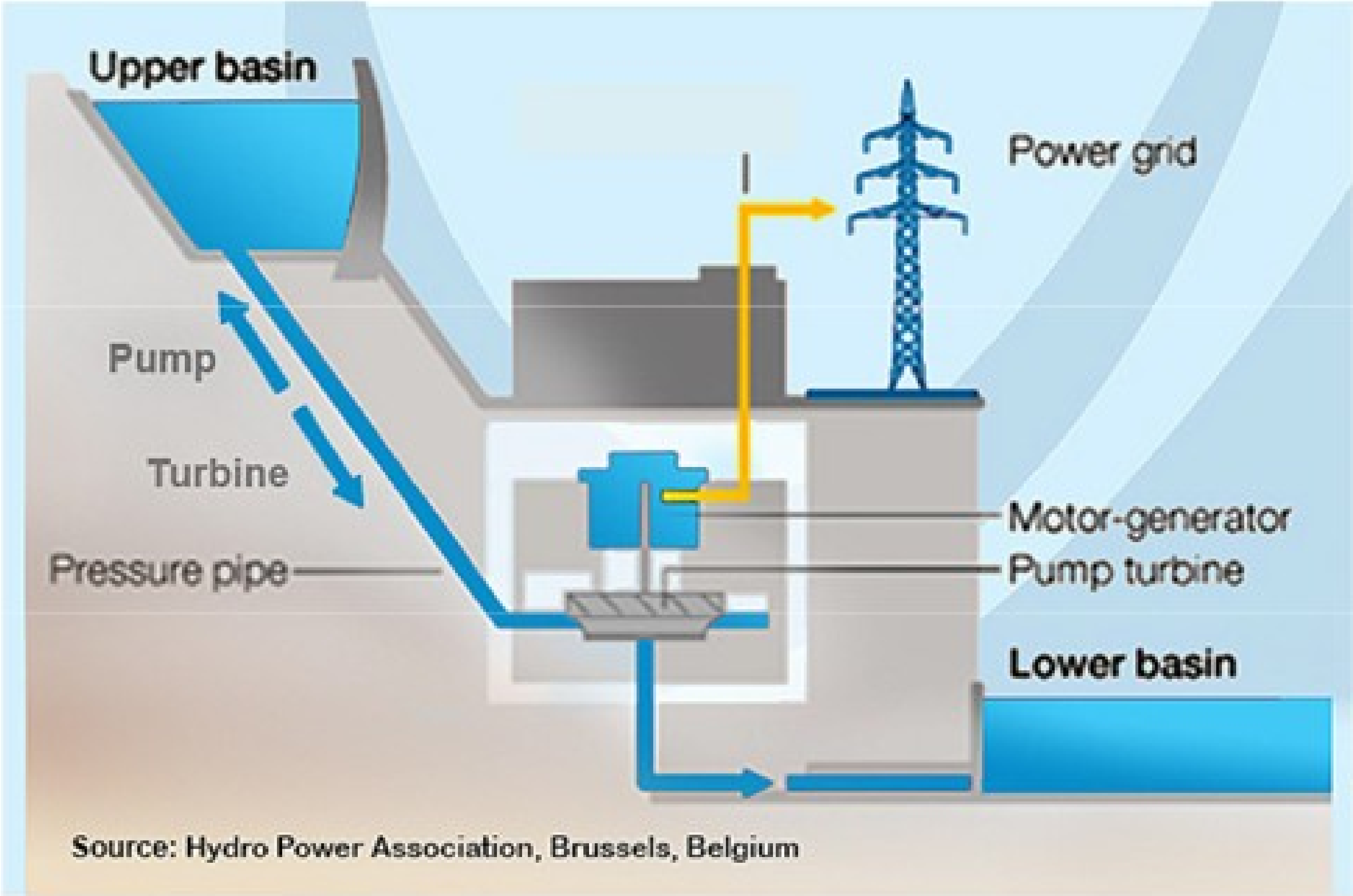
$\dot{Q}$: Water flow rate (m^3/s).

h: Head of water (m)

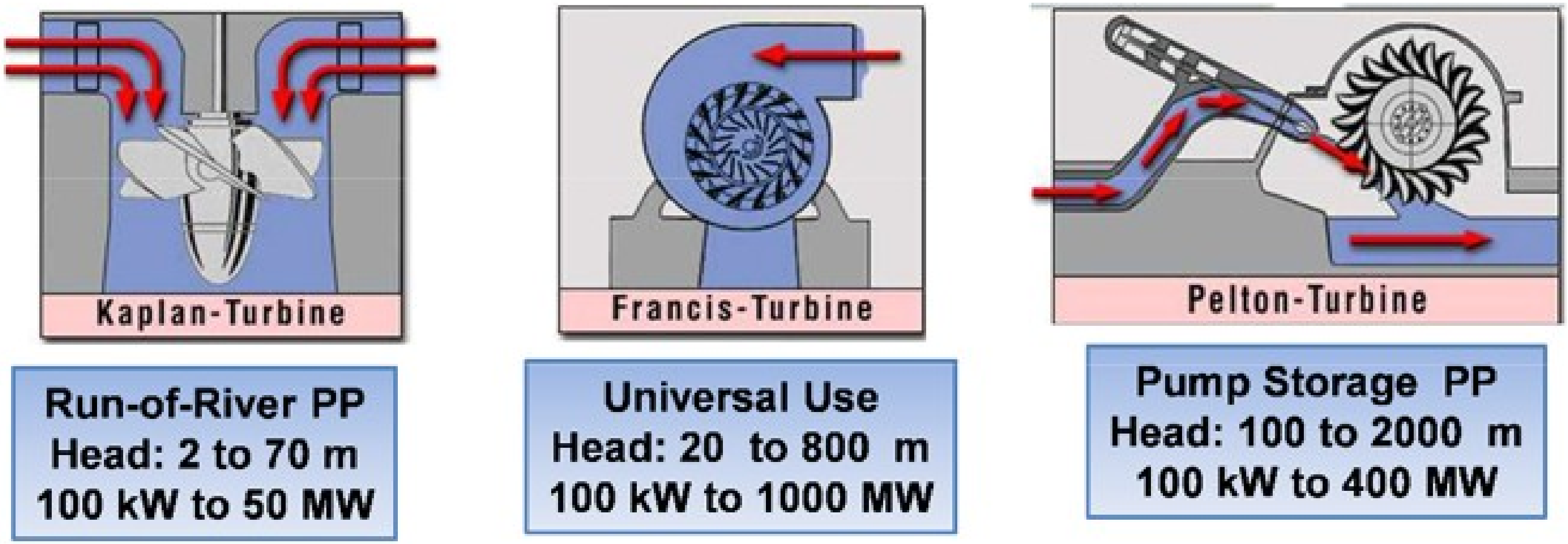




Pump hydro


Upper basin
Power grid
Pump
Turbine
Pressure pipe
Motor-generator
Pump turbine
Lower basin
Source: Hydro Power Association, Brussels, Belgium

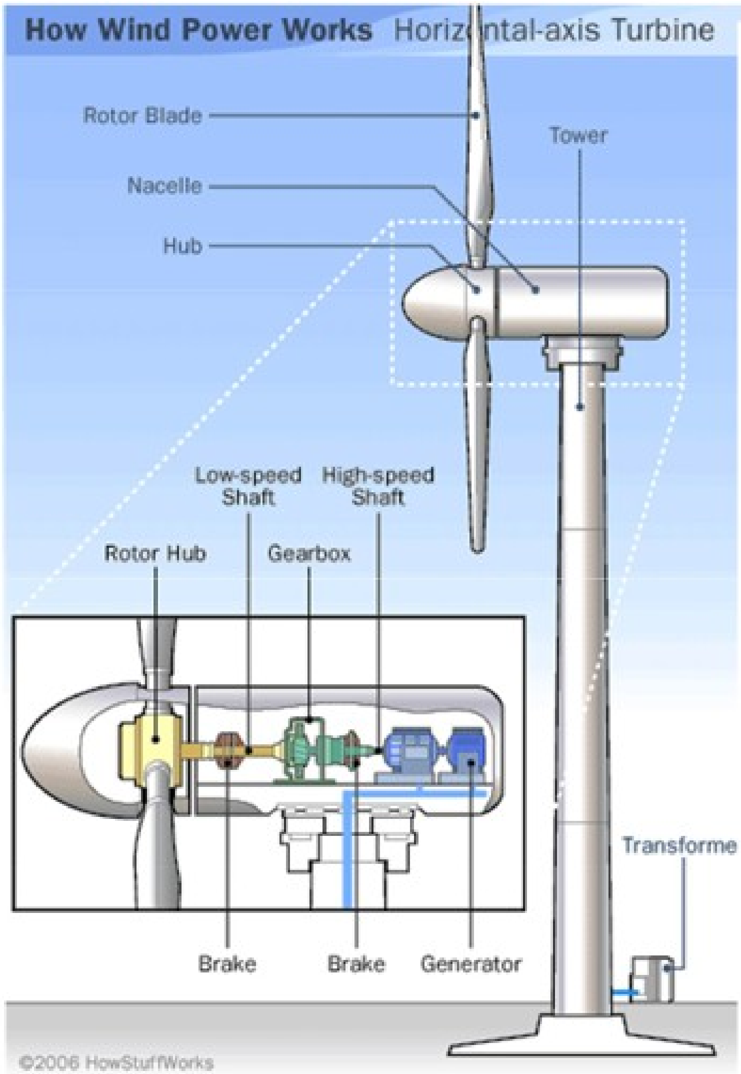
Different hydro turbines



Cost of hydro

Item	Unit	Run of River	Dam Hydro	Pump Storage
Technical Parameters				
Nominal power	MW	150	150	150
Load segment	-	base	Intermediate	peak
Typical full load utilization time	h / a	4,500	3,500	1,000
Annual electricity generation	GWh / a	675	525	150
Financial constraints				
Water head	m	20	200	250
Pumping electricity eta=85.0%	GWh /a	-	-	176
Pump utilization time	h / a	-	-	1,000
Cost of electricity for pumping	€ / MWh	-	-	30
Life time	a	50	50	50
Discount rate, in real terms	% / a	4.58%	4.58%	4.58%
Fixed OPEX	% Inv./ a	1.0	1.1	1.2
CAPEX, estimate, US$ 2014, ±25%	**Mio. €**	**525**	**600**	**675**
specific	€ / kW	3,500	4,000	4,500
Annual electricity gen. Costs, in real terms				
Capital costs 4.58%/a 50 a	Mio. € / a	26.9	30.7	34.6
Fixed OPEX	Mio. € / a	0.5	0.7	0.8
Variable Cost	Mio. € / a	-	-	5.3
Total annual costs	Mio. € / a	**27.4**	**31.4**	**40.7**
Levelized Electricity cost, real terms	**€ / MWh**	**40.62**	**59.80**	**271.19**
Capacity cost	€ / (KW a)	179.28	204.89	230.50
Variable cost	€ / MWh	-	-	35.29

Wind power

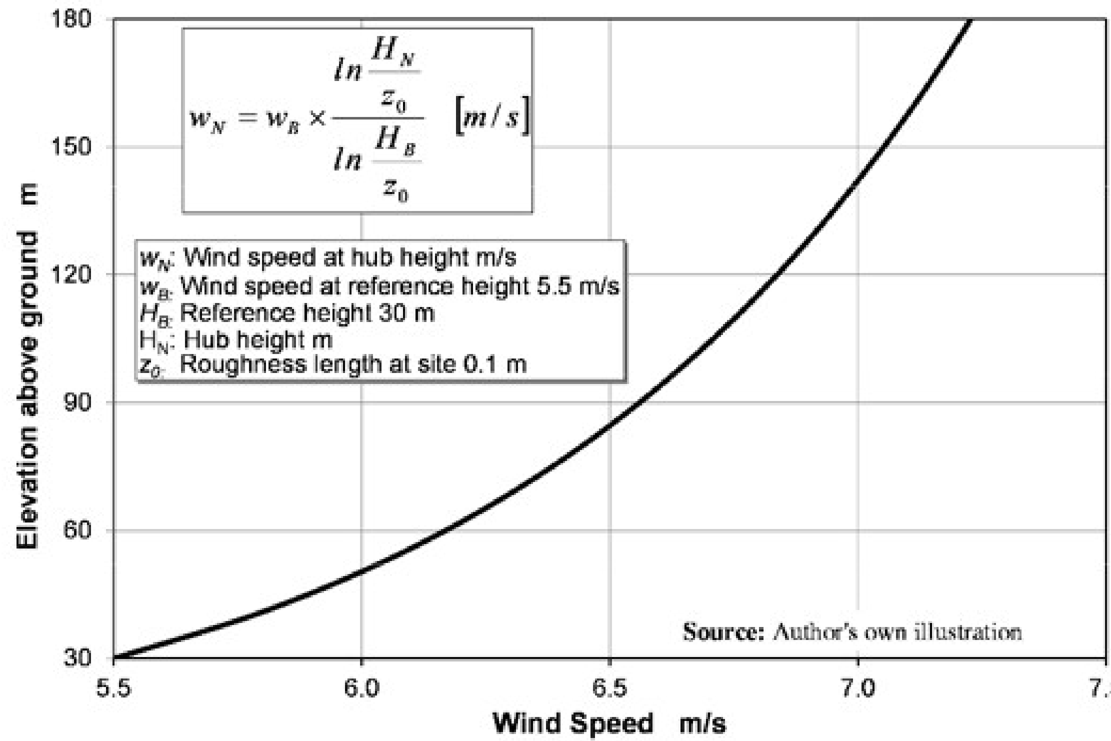


Source: http://www.howstuffworks.com/

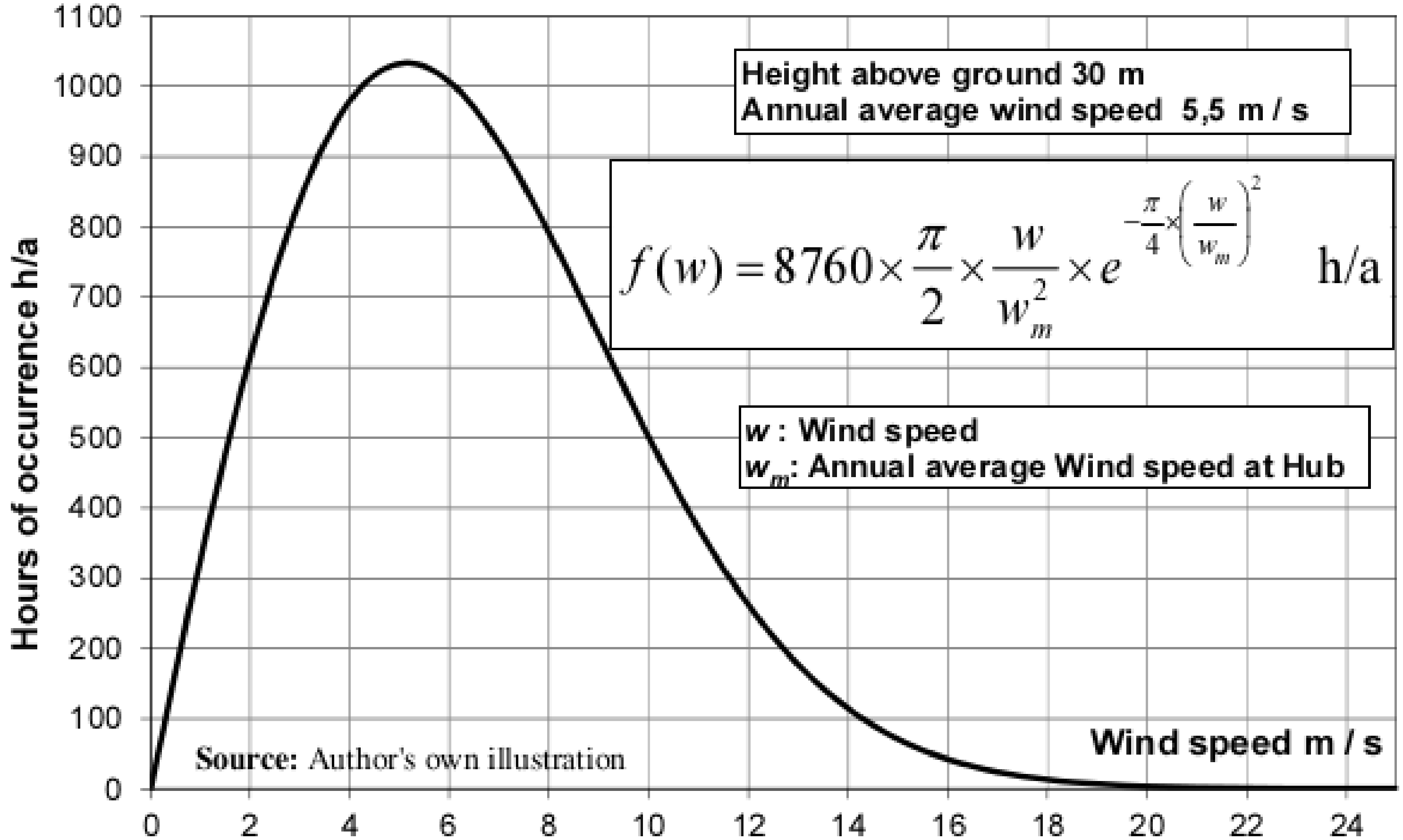
$$P = \frac{c_p}{8000} \cdot \pi \cdot \rho \cdot D^2 \cdot w^3 \quad [\mathrm{kW}]$$

Where:

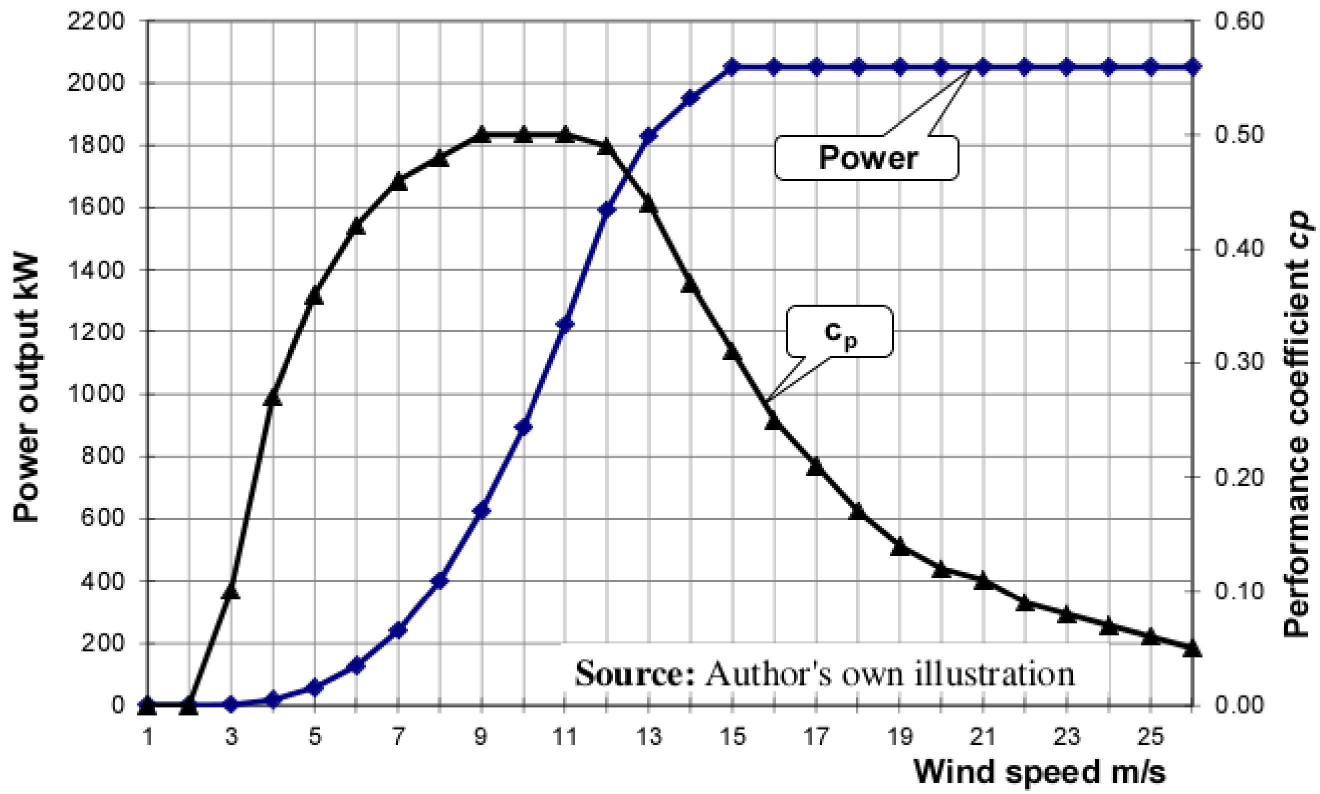
c_P: Actual performance coefficient of the wind turbine
ρ: Air density [kg/m³]
D: Rotor diameter [m]
w: Wind speed [m/s]



Rayleigh Freq Dist of Wind Speed



Performance curve



Parameter	Symbol	IEC-Wind Class			
		I	II	III	IV
Average wind speed	v_{ave}	10.0 m/s	8.5 m/s	7.5 m/s	6.0 m/s
Maximum, 10 minute average wind speed in a 50 year period	v_{50}	70.0 m/s	59.5 m/s	52.5 m/s	42.0 m/s
Air turbulence intensity at a wind speed of 15 m/s ***TI*** $_{15}$	A	18.0%			
	B	16%			
	C	14%			

Note: Wind speed at Hub height

Reference annual electricity yield

The computation of the annual electricity yield of a single wind turbine is conducted by multiplication of the power output values from the performance curve with the corresponding values of duration of each wind speed from the Weibull or Rayleigh distribution over all wind speed intervals.

Annual average wind speed $\boldsymbol{w}$**:**		5.5 m/s	30 m above ground
Rated power output		3,000	
Availability		0.97	
Hub height H_N**:**		149 m	
Average wind speed at hub height w_N**:**	Z0=0.10	7.05 m/s	Roughness class 2

w_N	m / s	0.0	1.0	2.0	3.5	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	**Sub - total**
P_e	kW	0	0	0	49	155	339	628	1,036	1,549	2,090	2,580	2,900	3,000	
t	h / a	0	273	520	799	861	933	941	894	806	693	570	450	341	
W_e	MWh	0	0	0	38	129	307	573	898	1,210	1,404	1,426	1,265	992	**8,243**

Continuation

w_N	m / s	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0	25.0	**Sub - total**
P_e	kW	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	
t	h / a	249	175	118	77	49	30	17	10	5	3	1	1	0	
W_e	MWh	724	509	345	225	142	86	51	29	16	8	4	2	1	**2,142**

Grand total, annual yield MWh		**10,385**
Capacity factor	**39.5%**	**3,462 h/a**

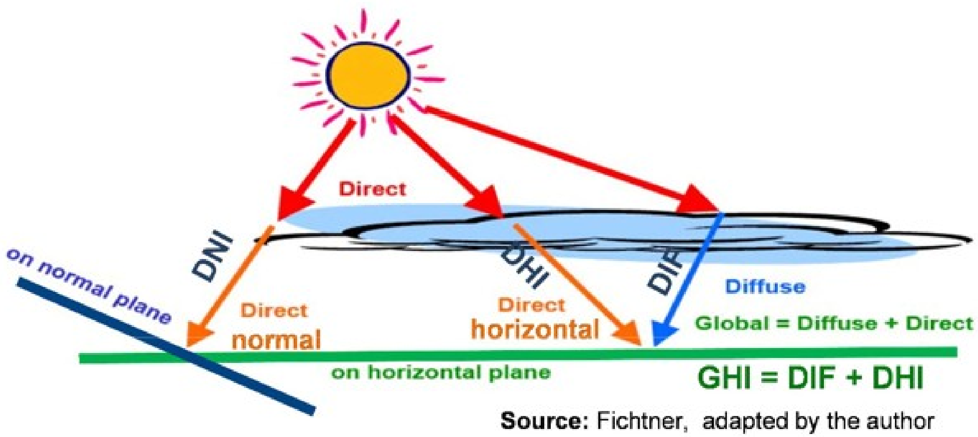
P_e kW: Performance characteristic of the WT *)

t h/a: Frequency distribution acc. Rayleigh Model

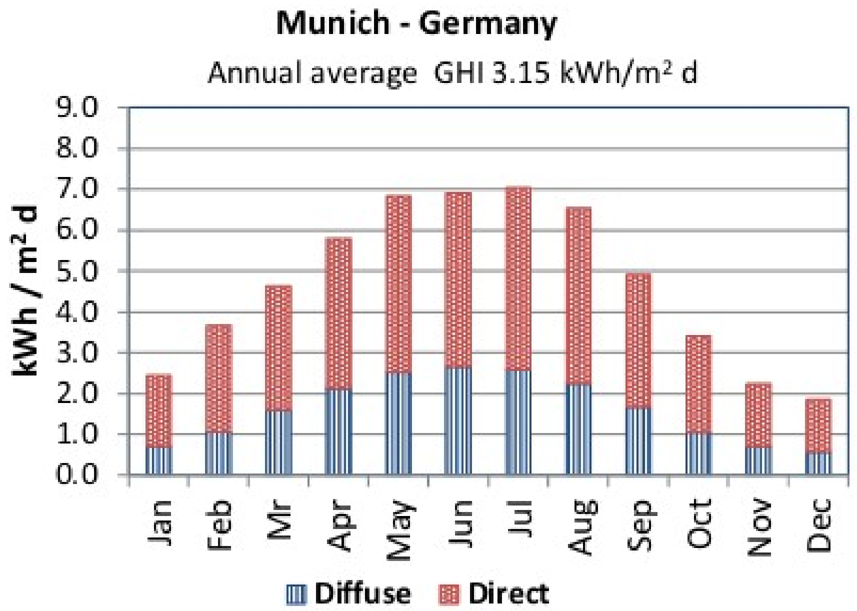
Electricity Generation Costs

Item	Unit	Wind farm Capacity	
		60 MW	120 MW
Technical, Operational parameters			
Average wind speed, 30 m above ground	m / s	5.5	5.5
Electrical capacity of each WT	kW	2,400	3,000
Number of wind turbines	Stck.	25	40
Energy yield of each WT	MWh/a	8,590	10,385
Total gross energy yield of the wind farm	MW	60.0	120.0
Energy losses of the wind farm	%	14%	13%
Electricity production, net	MWh/a	184,690	361,399
Full load hours	h/a	3,078	3,012
Technical, economic parameters			
Life time	a	20	20
Construction time	a	1.50	2.00
Inflation	%	2.0%	2.0%
Discount rate in real terms (WACC) *)	%	4.58%	4.58%
CAPEX estimate, 2013 prices, ±20%	**1,000 €**	**103,280**	**191,250**
Operating Costs	**1,000 €**	**5,354**	**10,131**
Maintenance contract	1,000 €	1,847	3,614
Management/technical surveillance	1,000 €	1,343	2,486
Insurance	1,000 €	516	956
Reserves for decommissioning	1,000 €	826	1,530
Costs of personnel	1,000 €	175	280
Leasing costs for site	1,000 €	646	1,265
Annualized CAPEX	**1,000 €**	7,642	14,151
Total annual costs	**1,000 €**	**12,996**	**24,282**
Specific electricity generation cost	**€ / MWh**	**70.36**	**67.19**

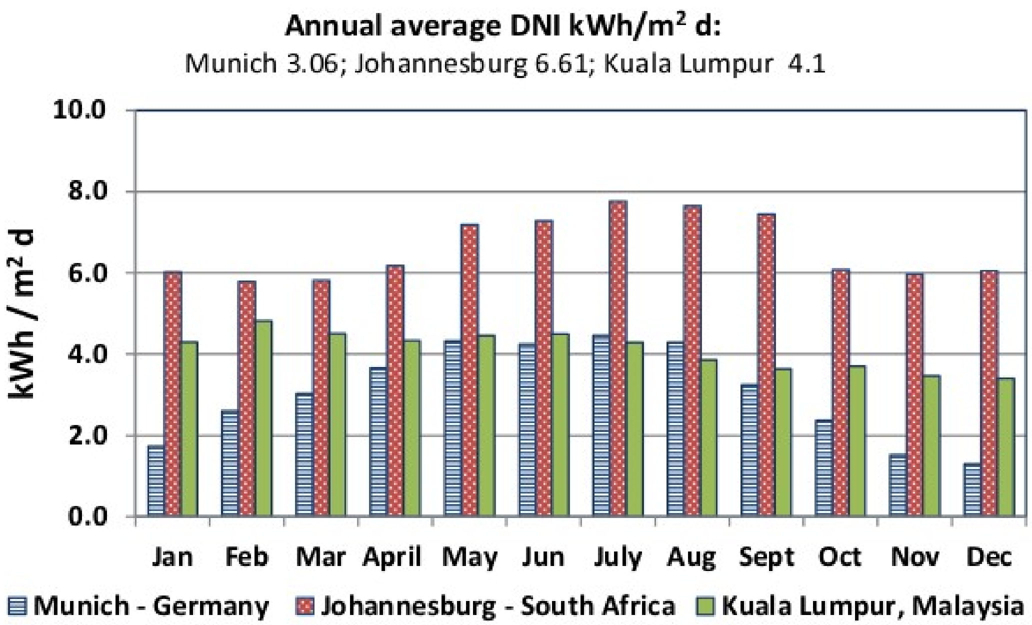
Solar



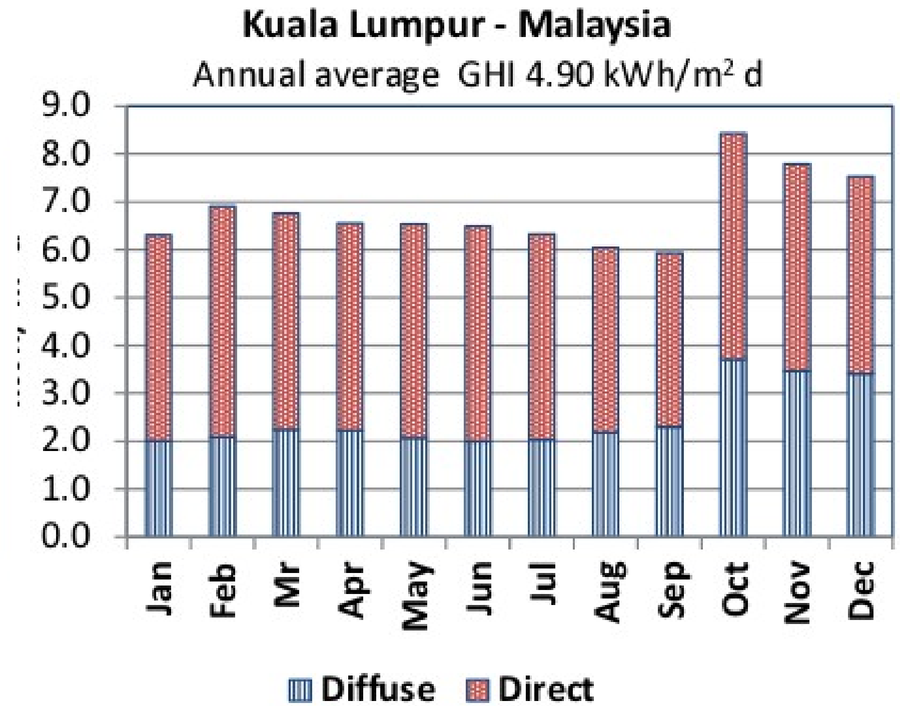
Direct
DNI
DHI
DIF
on normal plane
Direct
normal
Direct
horizontal
Diffuse
Global = Diffuse + Direct
on horizontal plane
GHI = DIF + DHI
Source: Fichtner, adapted by the author



Munich - Germany
Annual average GHI 3.15 kWh/m² d
kWh / m² d
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Jan Feb Mr Apr May Jun Jul Aug Sep Oct Nov Dec
Diffuse
Direct

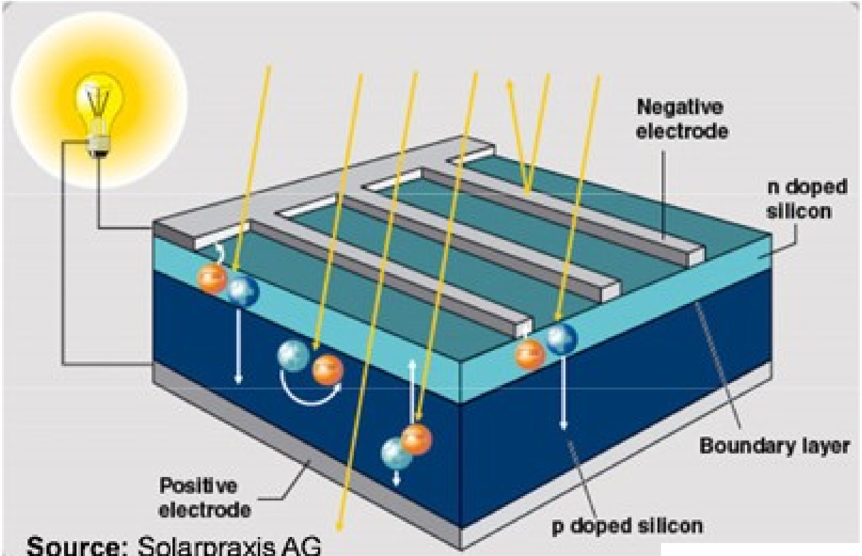


Annual average DNI kWh/m² d:
Munich 3.06; Johannesburg 6.61; Kuala Lumpur 4.1
kWh / m² d
10.0
8.0
6.0
4.0
2.0
0.0
Jan Feb Mar April May Jun July Aug Sept Oct Nov Dec
Munich - Germany
Johannesburg - South Africa
Kuala Lumpur, Malaysia



Kuala Lumpur - Malaysia
Annual average GHI 4.90 kWh/m² d
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Jan Feb Mr Apr May Jun Jul Aug Sep Oct Nov Dec
Diffuse
Direct

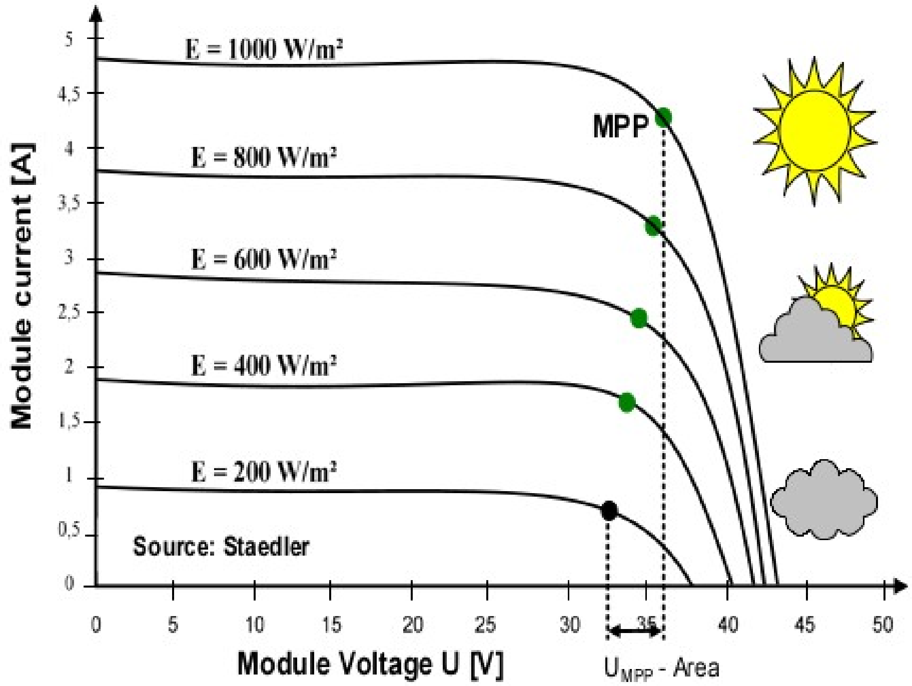
Solar - Photovoltaic



Source: Solarpraxis AG

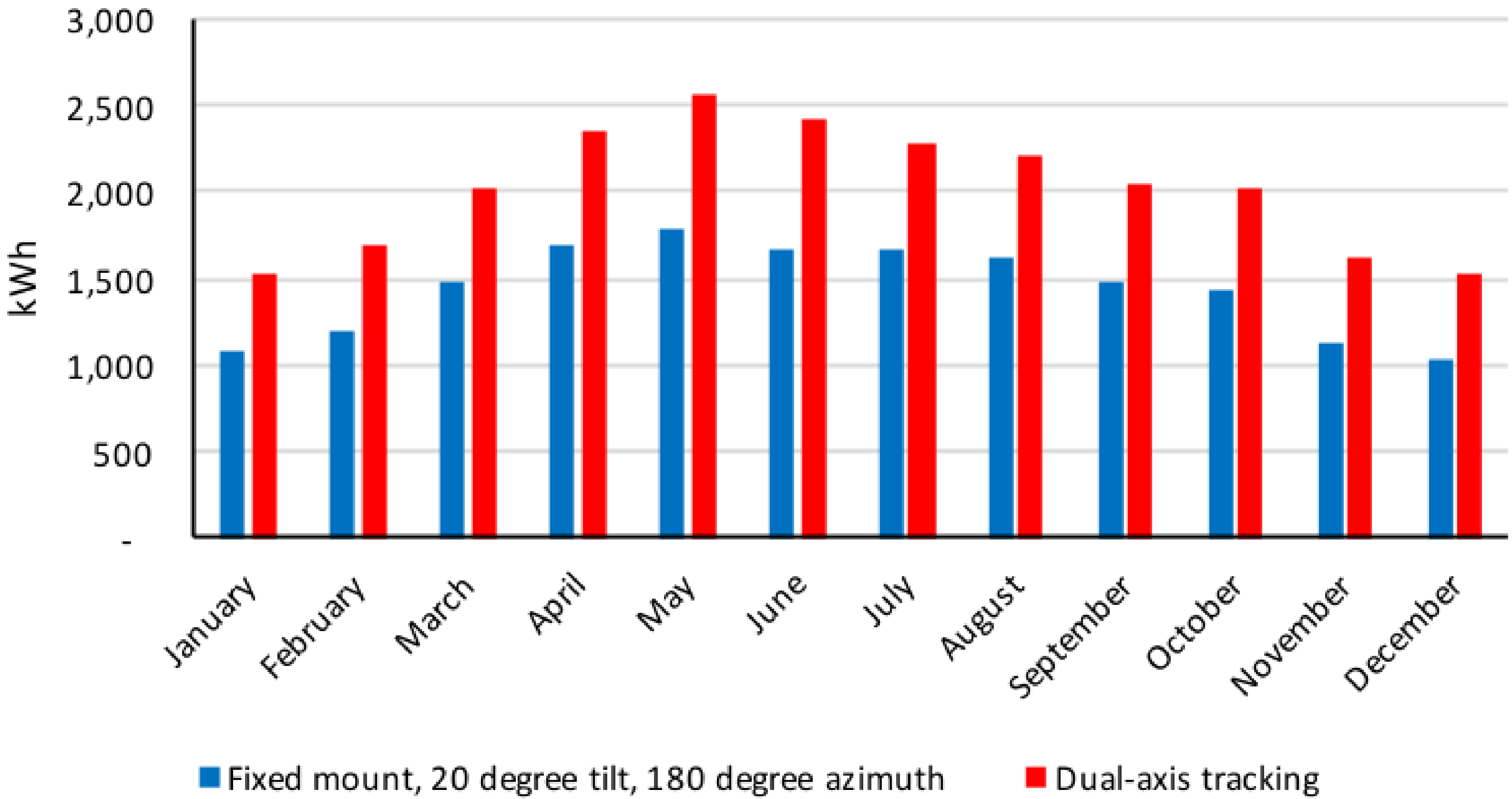
Material	Cell Efficiency %	Module Efficiency %
Crystalline Silicon Cells		
Mono-crystalline	16% to 22%	14% to 20%
Poly-crystalline	14% to 18%	12% to 16%
Thin Film Cells		
Amorphoua Silicon	8% to 10 %	7% to 9%
Cadmium Telluride – CdTe	10% to 17%	11% to 14%
Copper Indium – CIS, CIGS	11% to 14%	10% to 13%

Module voltage



Item	Unit	Values		
Cell temperature	°C	25	60	80
Crystalline cells				
Temperature Coefficient	%/K	-0.4		
Power output	kW	100	86	78
Thin film cells				
Temperature Coefficient	%/K	-0.25		
Power output	kW	100	91	86

Dual axis



3,000
2,500
2,000
1,500
1,000
500
-
kWh
January
February
March
April
May
June
July
August
September
October
November
December
Fixed mount, 20 degree tilt, 180 degree azimuth
Dual-axis tracking

Yield calculation

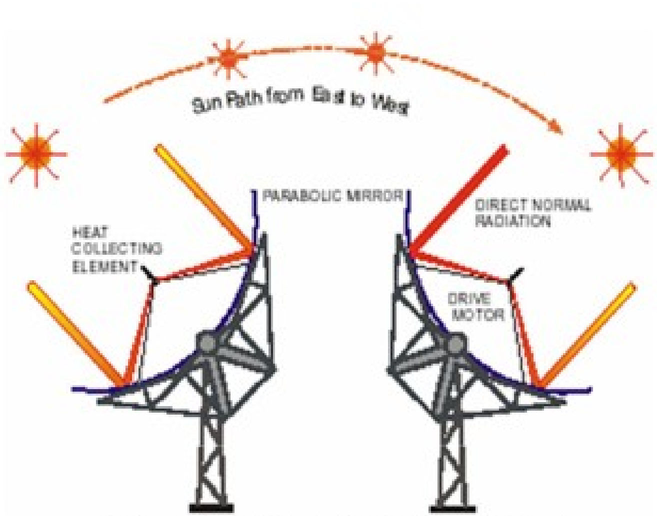
Item	Unit	Germany Munich	Greece Athens	Malysia Kuala Lumpur	Australia Sydney	S. Africa Johannes burg
Technical parameters						
Module area (mono-crystalline)	m^2	489,476				
PV Module efficiency η_M	-	20.43%				
Annual performance ratio *PR*	-	81.50%				
Azimuth *)	degrees	0				
Tracking	-	vertical axis tracking, optimal tilt				
Site latitude	degrees N	48.5	38.5	3.5	-33.5	-26.5
Longitude	degrees E	11.5	23.5	101.5	151.5	28.5
Optimal tilt angle, annual average ***)	-	37.9°	32.3°	14.6°	30.2°	25.9°
Electricity Production						
Nominal capacity STC **)	MW_p	100				
Horizontal global irradiation ***)	kWh /m^2 a	1,149	1,565	1,788	1,620	2,018
Global irradiation, optimal tilted panel ***)	kWh /m^2 a	1,321	1,748	1,821	1,862	2,306
Annual yield	MWh / a	107,661	142,462	148,411	151,753	187,939
Specific yield (1000 W/m^2, 25°C, AM =1.5))	kWh /kW_p	1,077	1,425	1,484	1,518	1,879

*) Northern hemisphere against due south, Southern hemisphere against due north

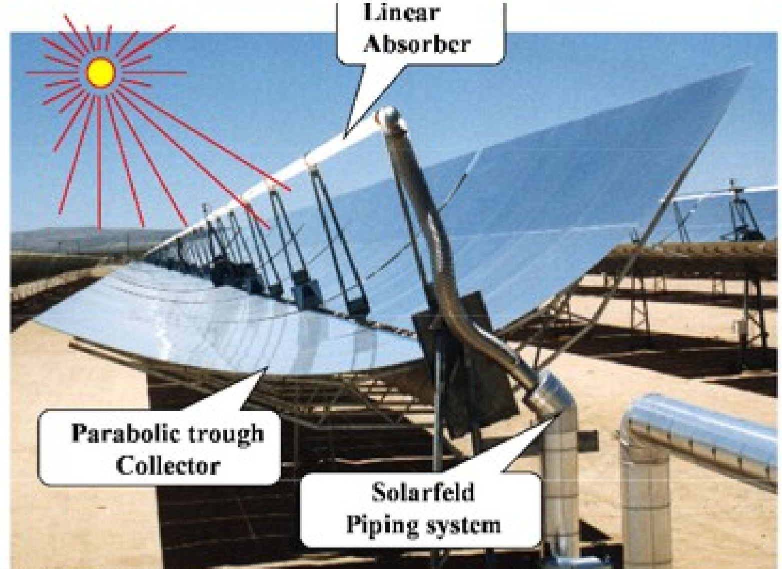
Levelized elec. costs

Item	Unit	Germany Munich	Greece Athens	Malysia Kuala Lumpur	Australia Sydney	S. Africa Johannes burg
		100 MWe				
Energy production						
Nominal capacity STC	MWp	100				
Annual yield	MWh / a	107,661	142,462	148,411	151,753	187,939
Financial constraints						
Life time	a	25				
Equity share	%	20.0%				
Inflation	% / a	2.0%				
Discount rate, nominal	% / a	7.5%				
Discount rate, real terms	% / a	5.4%				
O&M Cost	% / a	0.50%				
Site lease	ct / kWh	0.20	0.20	0.20	0.20	0.20
Insurance	% / a	0.75%	0.75%	0.75%	0.75%	0.75%
CAPEX, US$ 2014, ±20%	**Mio. US$**	**215.0**	**215.0**	**215.0**	**215.0**	**215.0**
Specific CAPEX	USD / KWp	2,150	2,150	2,150	2,150	2,150
Annual levelized costs, on real terms						
Annualized CAPEX	1000 US$ / a	15,809	15,809	15,809	15,809	15,809
O&M Costs	1000 US$ / a	1,075	1,075	1,075	1,075	1,075
Lease	1000 US$ / a	215	285	297	304	376
Insurance	1000 US$ / a	1,612	1,612	1,612	1,612	1,612
Total	**1000 US$ / a**	**18,712**	**18,781**	**18,793**	**18,800**	**18,872**

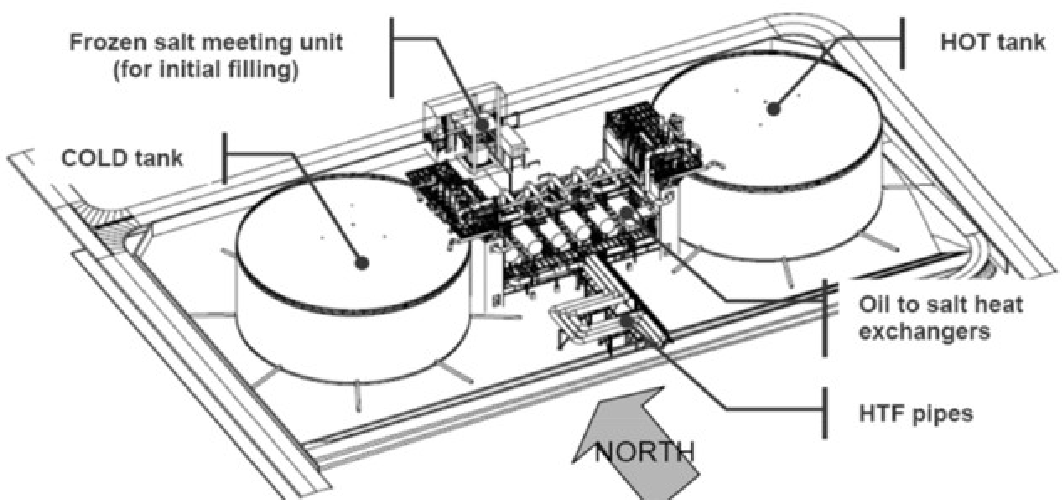
Concentrated



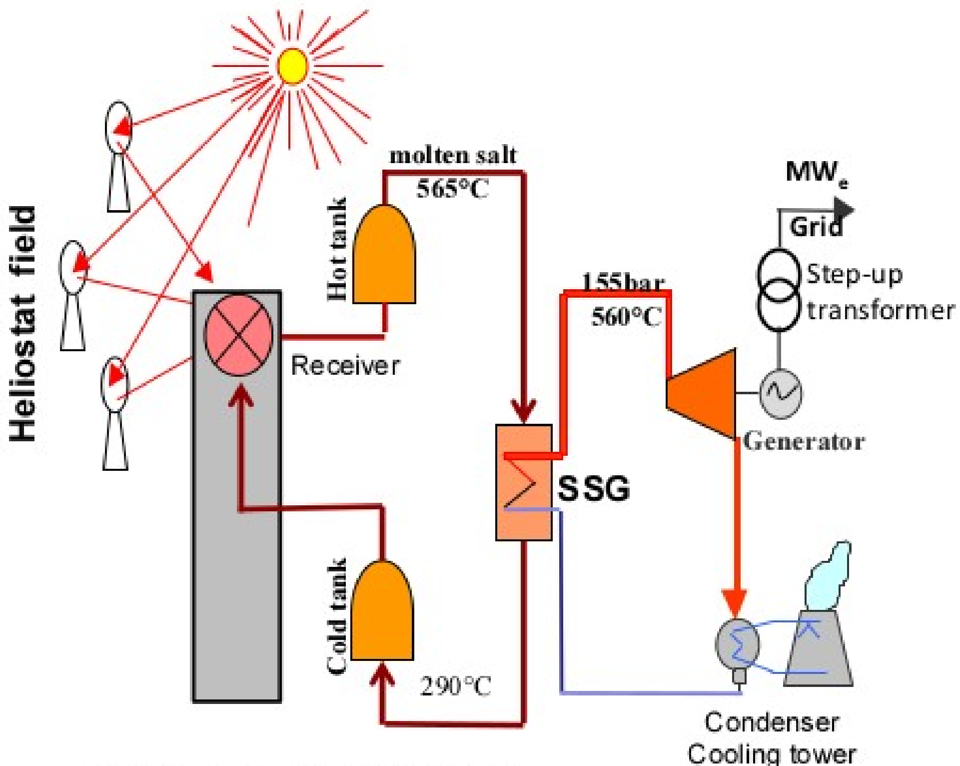
Solar collector tracking system
Source: Concentrated Solar Power



Source: Fichtner



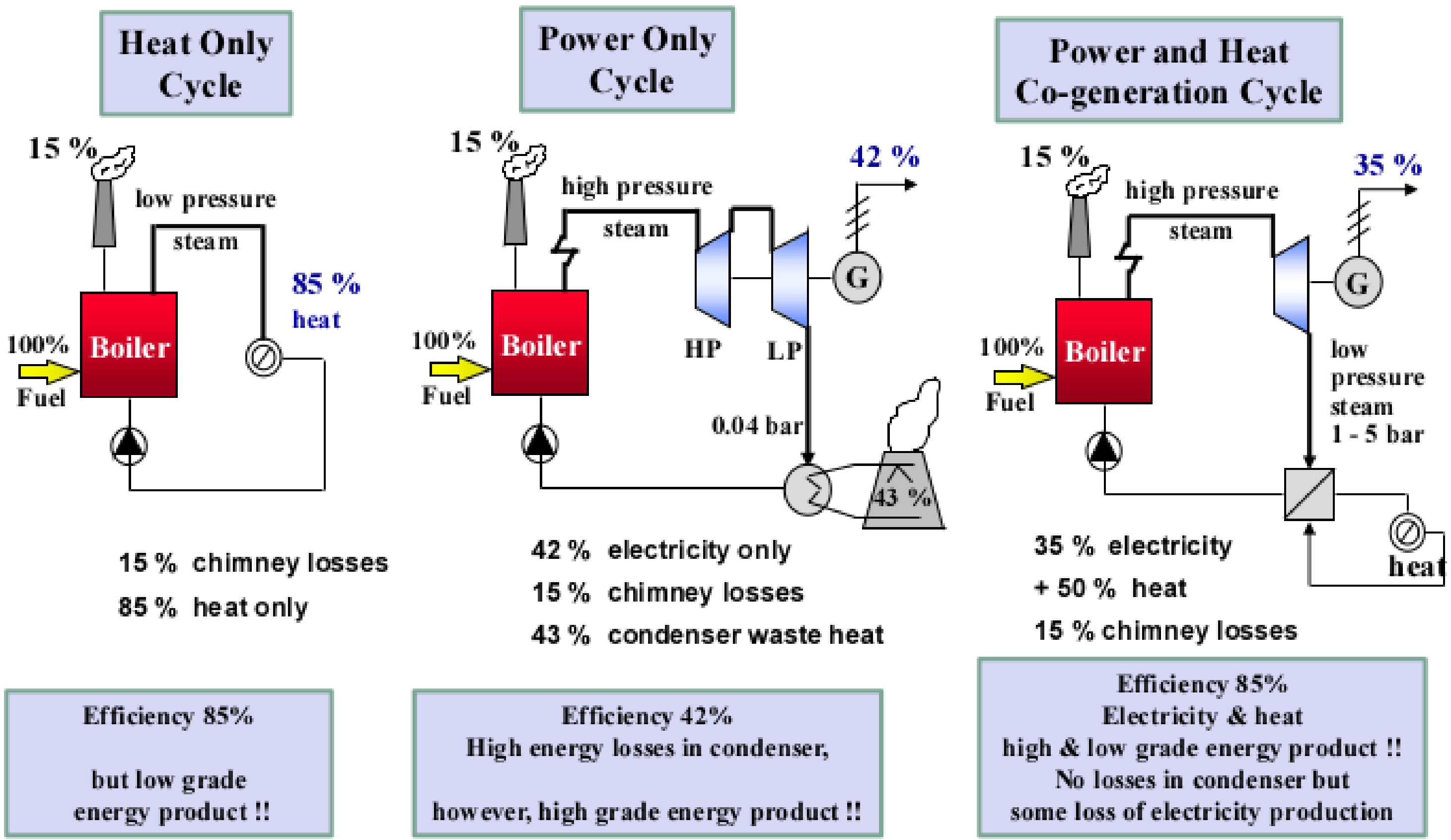
Solar tower



Source: Technologies & Economics
Author's own illustration

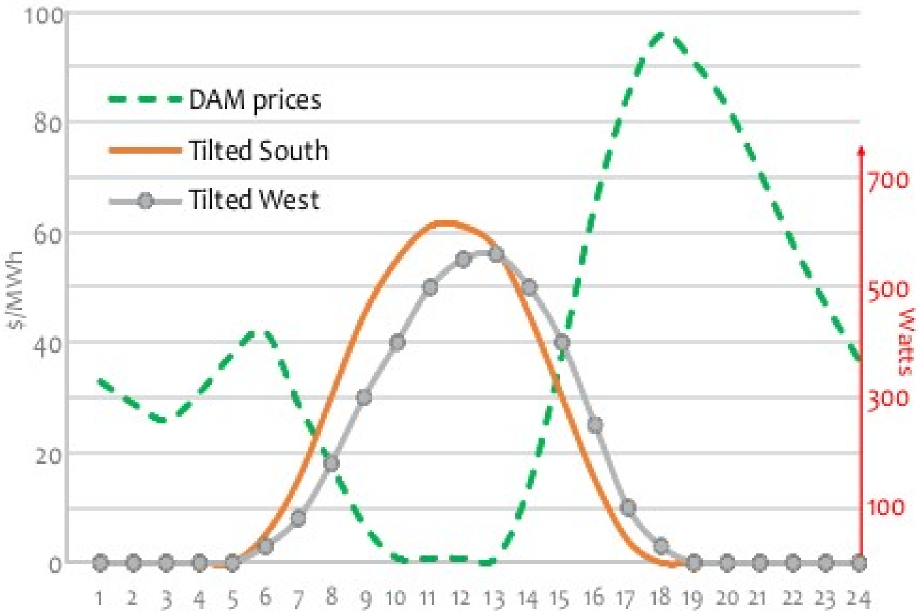
Item	Einheit Unit	100 MW		
		TES 9 h	TES 12 h	TES 15 h
Technical parameters				
Rated power output	MW	100		
Site latitude	grd	28		
Number of heliostats	-	7,158	8,978	11,07
Solar irradiation	kWh / m² a	2,400		
Net electricity production	GWh /a	379.6	476.2	587
Financial parammeters				
Discount rate in real terms	-	4.6%		
Project lifetime	a			2
CAPEX, US$ 2014, ±20	**mln US$**	**784**	**933**	**1,09**
Electricity generation costs in real terms				
Annual costs	mln US$ /a	66.9	79.4	92
of which capital cost		79.7%	79.9%	80.1
Levelized electricity cost	**US$ / MWh**	**176.3**	**166.7**	**158**

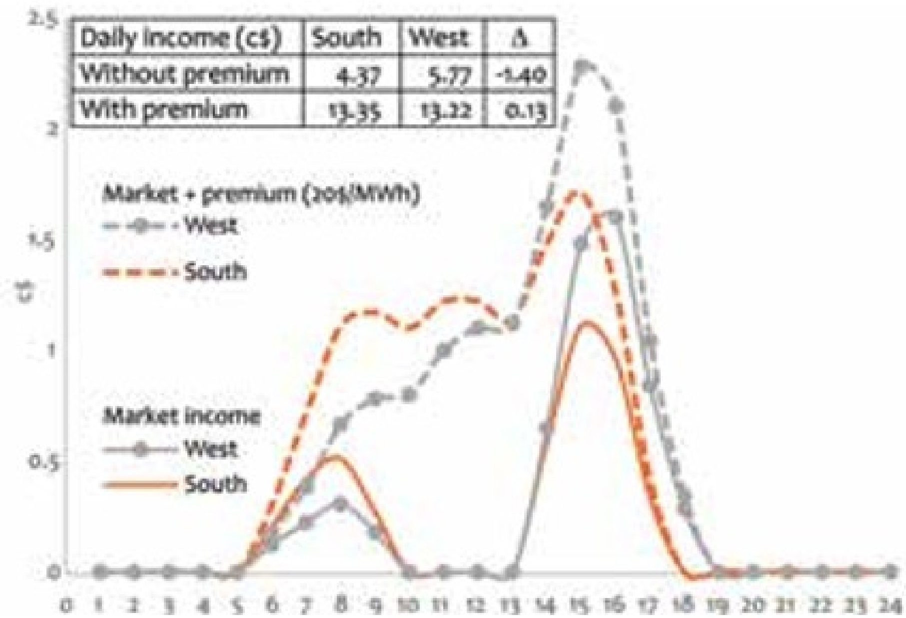
Cycles



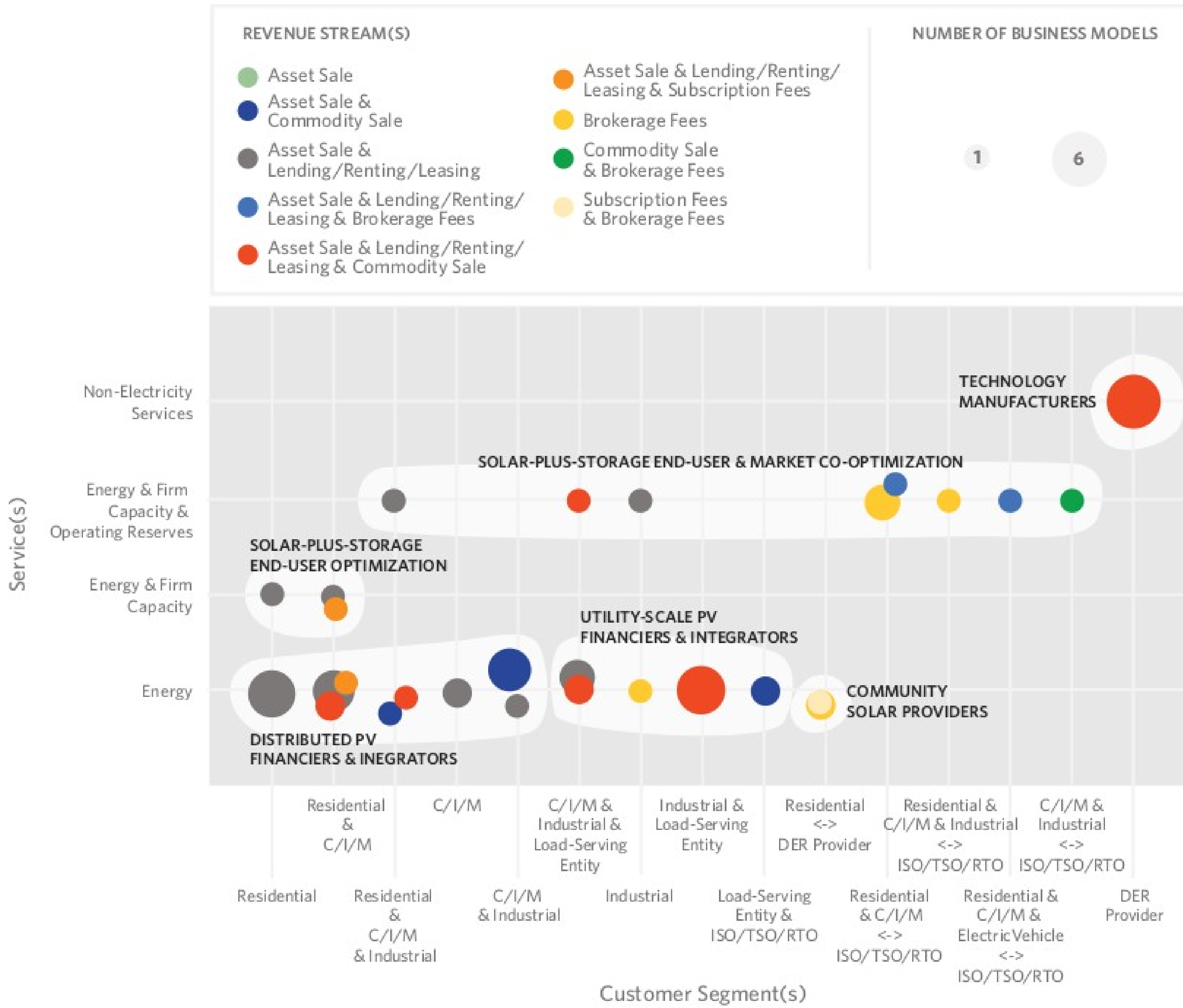
Source: Technologies & Economics, Author's own illustrations

South or West

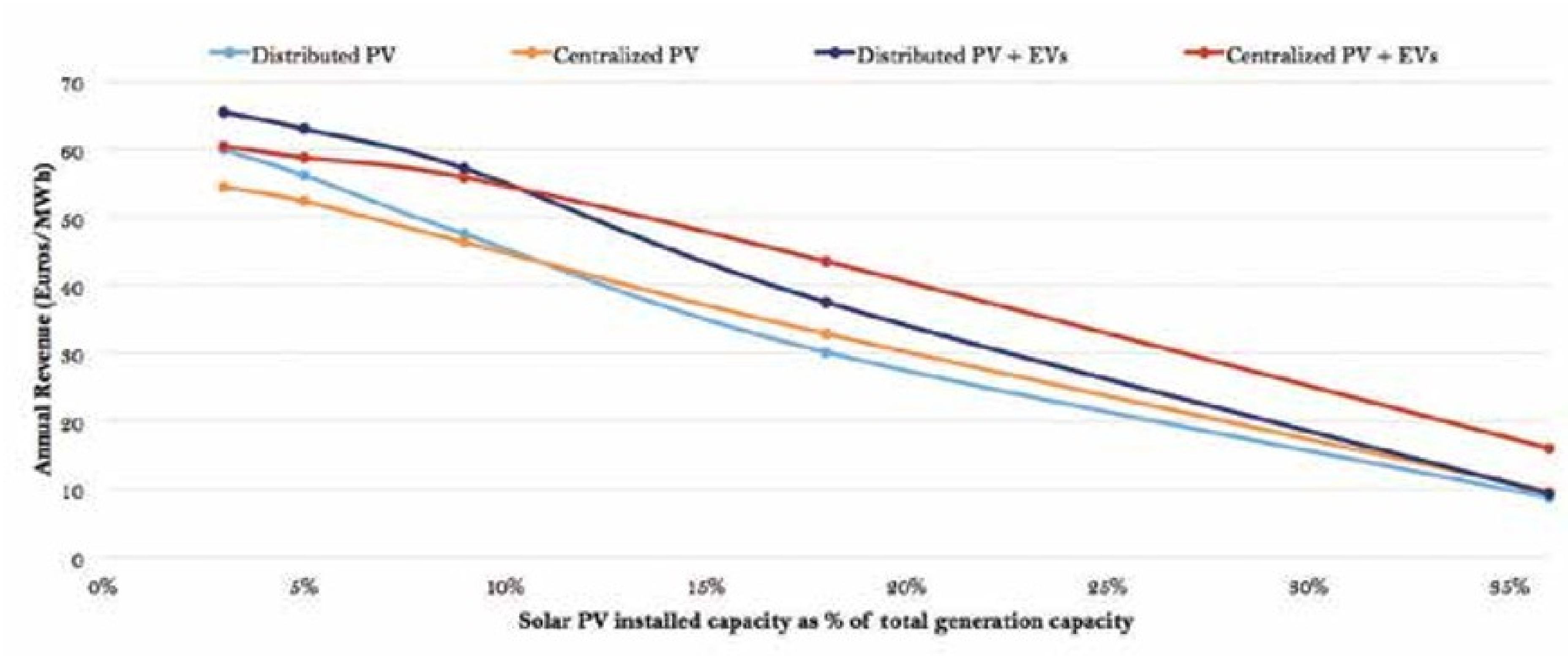




Taxonomy of Solar PV and Solar-plus-Storage Business Models

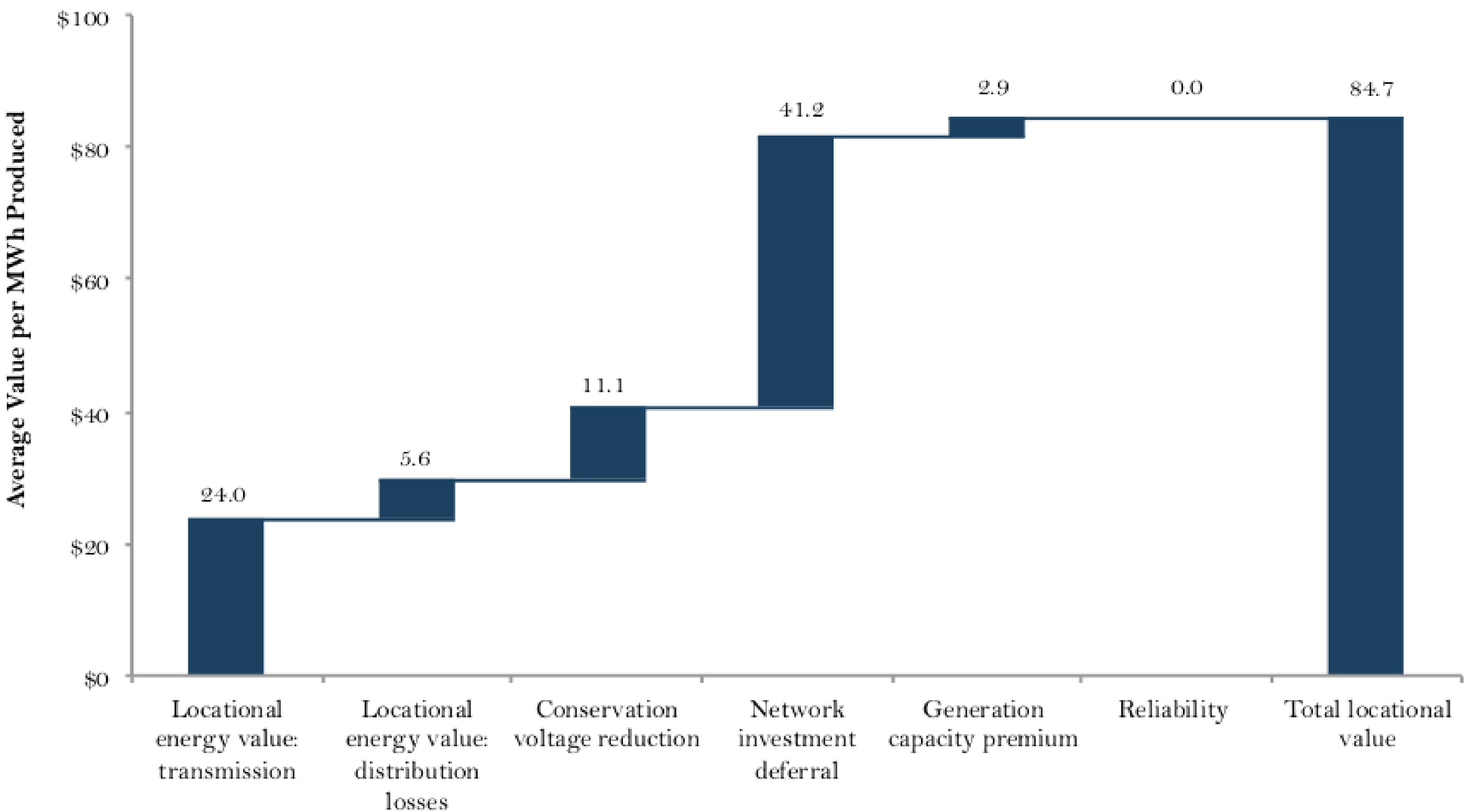


Solar revenue vs penetration

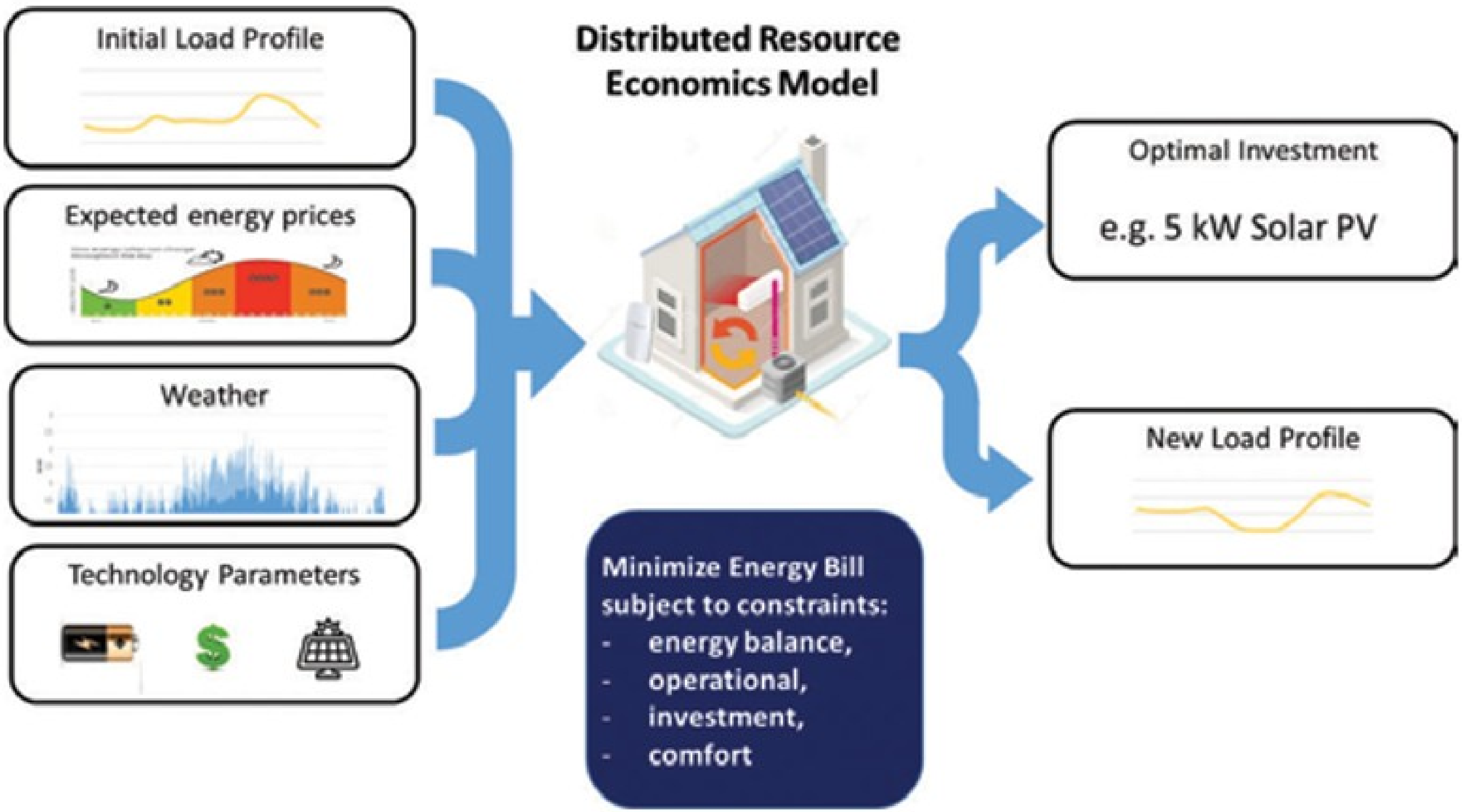


Locational value

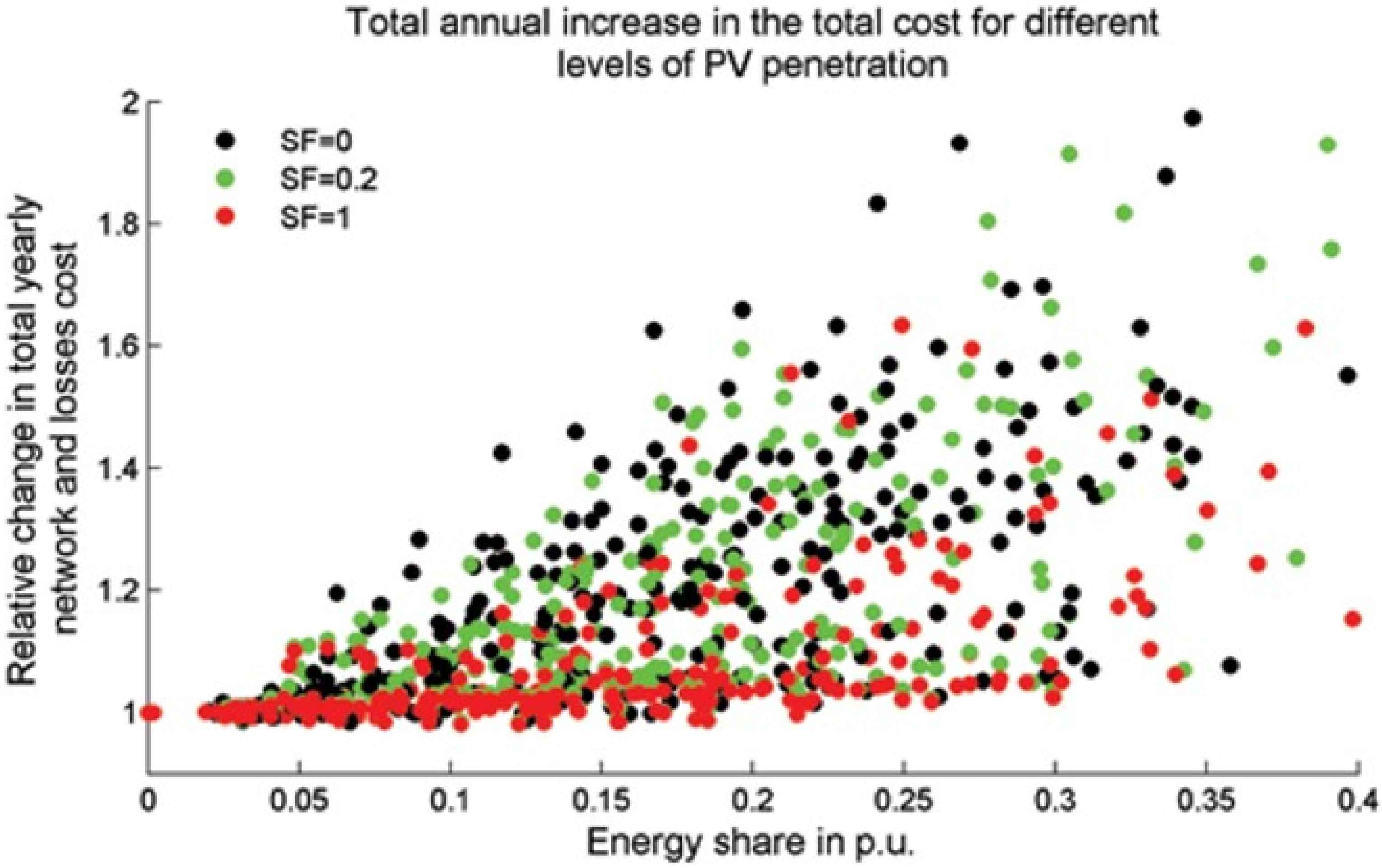
Figure 8.12: Locational Value of Distributed Solar PV — Long Island, New York (High-Value Example)



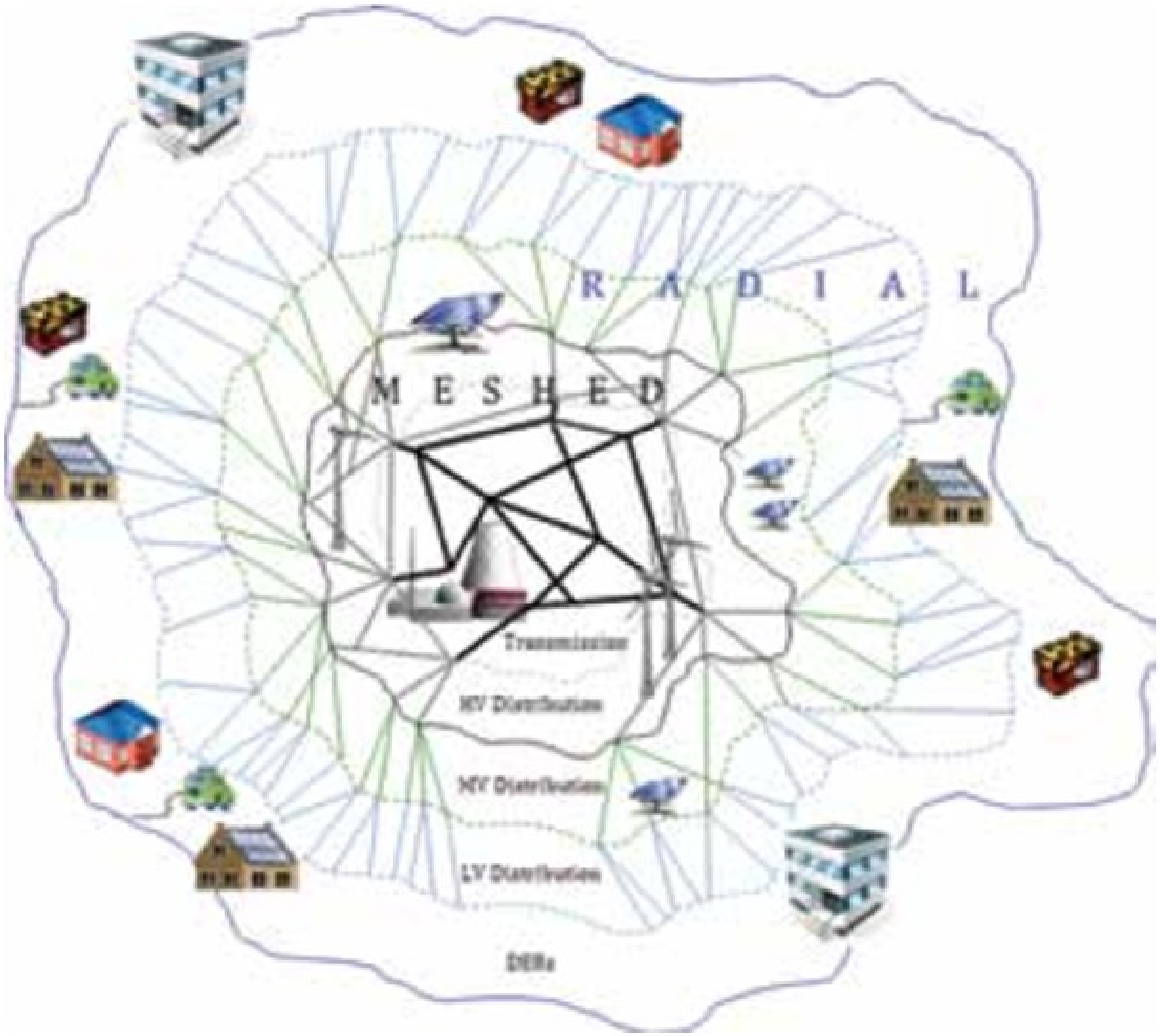
Distributed system



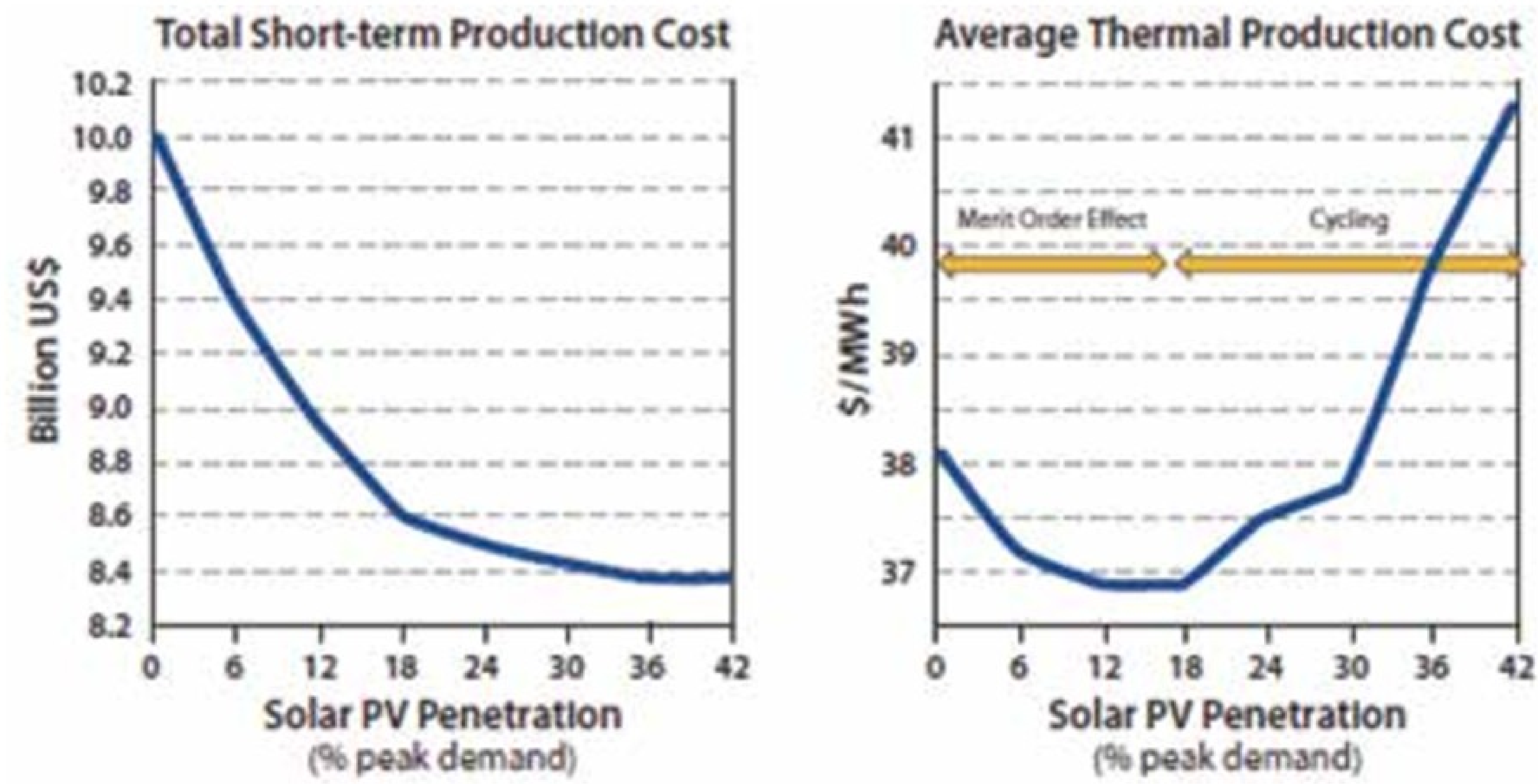
Increased penetration



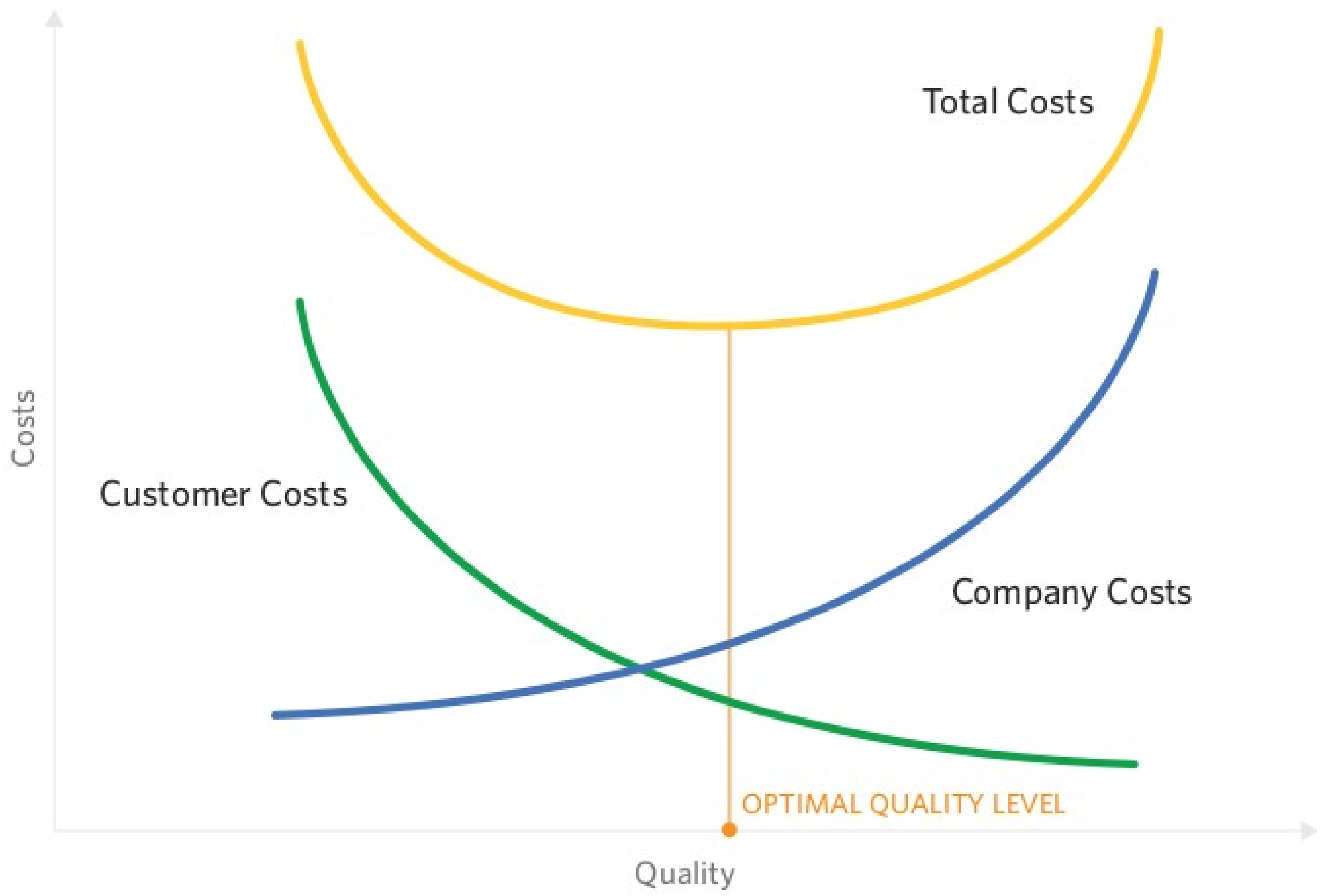
Technology on Grid



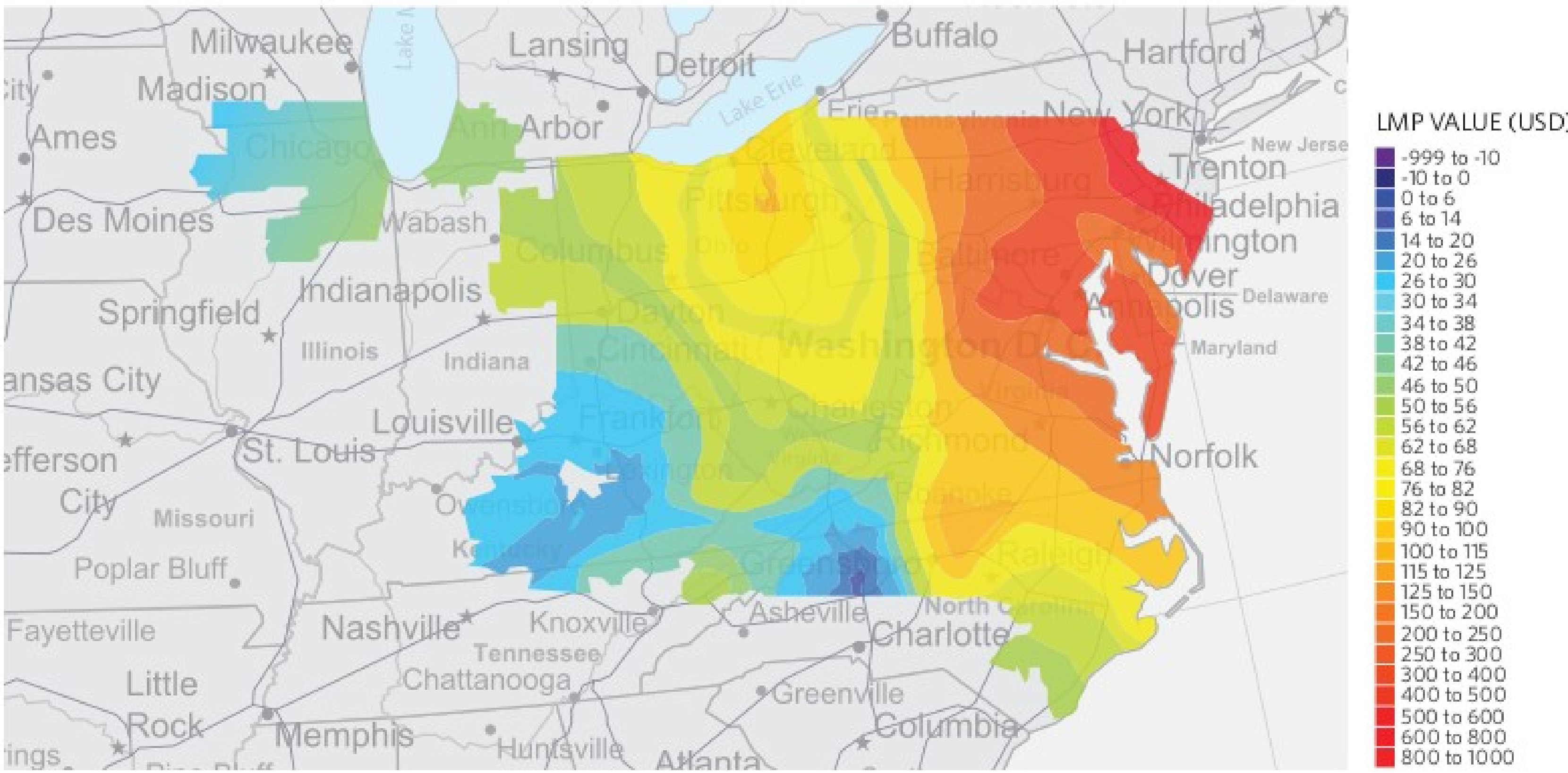
Production cost



Quality requirements



Nodal pricing



Source: PJM

Thank you

- For more info

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